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Epigraph: the final verse of the Diamond Sutra, as translated by Kenneth Saunders, in *The Wisdom of Buddhism*, ed. Christmas Humphreys (London: Curzon Press, 1987), p. 122.

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FOREWORD

Maps of Time unites natural history and human history in a single, grand, and intelligible narrative. This is a great achievement, analogous to the way in which Isaac Newton in the seventeenth century united the heavens and the earth under uniform laws of motion; it is even more closely comparable to Darwin's nineteenth-century achievement of uniting the human species and other forms of life within a single evolutionary process.

The natural history that David Christian deals with in the first chapters of this book is itself radically extended and transformed from the natural history of earlier ages. It starts with the big bang some 13 billion years ago, when, according to twentieth-century cosmologists, the universe we inhabit began to expand and transform itself. Processes thereby inaugurated are still in course, as time and space (perhaps) began, allowing matter and energy to separate from one another and distribute themselves throughout space in different densities and with different rates of energy flows in response to a variety of strong and weak forces. Matter, gathering into local clots under the influence of gravity, became radiant stars, clustered into galaxies. New complexities, new flows of energy arose around such structures. Then, some 4.6 billion years ago, around one star, our sun, planet Earth formed and soon became the seat of still more complicated processes, including life in all its forms. Humankind added yet another level of behavior a mere 250,000 years ago, when our use of language and other symbols began to introduce a new capacity for what Christian calls "collective learning." This in turn made human societies uniquely capable of concerting common effort so as to alter and sporadically expand widely varying niches in the ecosystem around each of them and, by now, surround us all in the single, global system.

The human history that Christian thus fits into the recently elaborated natural history of the universe is also an intellectual creation of the twentieth century. For while the efforts of physicists, cosmologists, geologists, and biologists were making the natural sciences historical, anthropologists, archaeologists, historians, and sociologists were busy enlarging knowledge about the human career on earth. They extended it back in time and expanded it pretty well across the face of the earth to embrace foragers, early farmers, and other peoples who left no written records and had therefore been excluded from document-based "scientific" history in the nineteenth century.

Most historians, of course, paid no attention to "prehistory," or to the lives of illiterate peoples, busy as they were with their own professional debates. Across the twentieth century, those debates, and the study of abundant Eurasian and a few African and Amerindian texts, added substantially to the sum of historical information and to the scope of our ideas about the accomplishments of the urbanized, literate, and civilized peoples of the earth. A few world historians, like myself, tried to weave those researches together into a more adequate portrait of humanity's career as a whole; and some also explored the ecological impact of human activity. I even wrote a programmatic essay, "History and the Scientific Worldview" (*History and Theory* 37, no. 1 [1998]: 1–13), describing what had happened to the natural sciences and challenging historians to generalize boldly enough to connect their discipline with the historicization of the natural sciences that had taken place behind our backs. Several scholars are, in fact, working toward that end, but only when I began to correspond with David Christian did I discover a historian who was already writing such a work.

The truly astounding dimension of Christian's accomplishment is that he finds similar patterns of transformation at every level. Here, for example, is what he says about stars and cities:

> In the early universe, gravity took hold of atoms and sculpted them into stars and galaxies. In the era described in this chapter, we will see how, by a sort of social gravity, cities and states were sculpted from scattered communities of farmers. As farming populations gathered in larger and denser communities, interactions between different groups increased and the social pressure rose until, in a striking parallel with star formation, new structures suddenly appeared, together with a new level of complexity. Like stars, cities and states reorganize and energize the smaller objects within their gravitational field. (p. 245)

Or weigh the words with which he closes this extraordinary book:

> Being complex creatures ourselves, we know from personal experience how hard it is to climb the down escalator, to work against the universal

> slide into disorder, so we are inevitably fascinated by other entities that appear to do the same thing. Thus this theme—the achievement of order despite, or perhaps with the aid of, the second law of thermodynamics—is woven through all parts of the story told here. The endless waltz of chaos and complexity provides one of this book's unifying ideas. (p. 511)

I venture to say that Christian's discovery of order amid "the endless waltz of chaos and complexity" is not just one among other unifying themes, but the supreme achievement of this work.

Here, then, is a historical and intellectual masterpiece: clear, coherent, erudite, elegant, venturesome, and concise. It offers his readers a magnificent synthesis of what scholars and scientists have learned about the world around us in the past hundred years, showing how strangely, yet profoundly, human societies remain a part of nature, properly at home in the universe despite our extraordinary powers, unique self-consciousness, and inexhaustible capacity for collective learning.

Perhaps I should conclude this introduction with a few words about who David Christian is. First of all, he has an international identity, being the son of an English father and an American mother who met and married in Izmir, Turkey. His mother, however, returned to Brooklyn, New York, for the birth of her son in 1946, while her husband, after discharge from his wartime duties in the British army, joined the colonial service and became a district officer in Nigeria. His wife quickly joined him there, so David's childhood was spend up-country in Nigeria until, at age 7, he went away to boarding school in England. Then, in due course, he went up to Oxford, getting a B.A. in modern history in 1968. (At Oxford this means mastering isolated segments from the history of England since Roman times along with a scattering of other fields in European history and even a few decades sliced from the American past: the very antithesis of "big history.") For the next two years, he took a job as a tutor at the University of Western Ontario in Canada, and earned an M.A. degree there. By then he had decided to specialize in Russian history and returned to Oxford, where a thesis on administrative reforms under Tsar Alexander I won him a D.Phil. in 1974. Like his father, he married an American wife; they have two children.

Between 1975 and 2000 he taught Russian history at Macquarie University in Sydney, Australia, along with other courses in Russian literature and European history. Influenced by the Annales school in France, his interests shifted to everyday aspects of Russian lives. Two books resulted, both dealing with what Russians put into their mouths: *Bread and Salt: A Social* *and Economic History of Food and Drink in Russia* (1985, coauthored with R. E. F. Smith) and *Living Water: Vodka and Russian Society on the Eve of Emancipation* (1990). These books soon attracted invitations to write more general works: first *Power and Privilege: Russia and the Soviet Union in the Nineteenth and Twentieth Centuries* (1986), then *A History of Russia, Central Asia, and Mongolia,* volume 1, *Inner Eurasia from Prehistory to the Mongol Empire* (1998).

The broad geographical and temporal sweep of the last of these books already reflected a teaching venture he launched in 1989 when, in the course of a discussion about what sort of introduction to history the department at Macquarie ought to provide for its students, David Christian blurted out something like "Why not start at the beginning?" and promptly found himself invited to show his colleagues what that might mean. Unlike every other historian who ever tried to teach human history on a world scale, Christian decided to begin with the universe itself; and with help from colleagues in other departments of the university, who lectured on their own scientific specialties, he staggered through the first year of what he jestingly chose to call "big history."

From the start, big history attracted a large and what soon became an enthusiastic student following. But his most responsive professional audience first arose in the Netherlands and in the United States, where news of what David Christian was doing persuaded a handful of venturesome teachers to launch parallel courses. The World History Association as well as the American Historical Association took note by devoting a session to big history at their annual meetings in 1998. Three years later David Christian decided to accept an invitation to come to San Diego State University and bring big history with him.

Other professional interests remain active. A second volume of his *History of Russia, Central Asia, and Mongolia* is in the works; so is an account of the Russian campaign to ban alcohol that peaked in the early 1920s. In his spare time David Christian has also written several important articles on scale in the study of history and a variety of other subjects. He is, in short, a historian of altogether unusual energy, daring, and accomplishment.

You, who are about to peruse this book, have a great experience before you. Read on, wonder, and admire.

William H. McNeill
22 October 2002

ACKNOWLEDGMENTS

A project like this turns a person into a magpie. You collect ideas and information voraciously; and after a bit you can start to forget each particular act of intellectual larceny. Fortunately for me, most scholars are (despite popular reputation) astonishingly generous with their time and ideas. I have benefited from this generosity particularly at the two institutions at which I have spent most of my career: Macquarie University in Sydney and San Diego State University in California. I will try to acknowledge as many debts as I can, but there are many more that I cannot acknowledge because I cannot remember them. Suggestions, approaches, book references have been tucked away in my mind so securely that I cannot remember where I got them; sometimes I may even be tempted to think of them as my own discoveries. Where such memory lapses have happened (and I am sure they often have), I can only apologize and express a generalized thanks to those friends and colleagues who have had the patience to discuss with me the large-scale historical problems that have fascinated me now for more than a decade.

I would particularly like to thank Chardi, who is a professional storyteller and a Jungian. She persuaded me that I was really teaching a creation myth. I also want to thank Terry (Edmund) Burke, who teaches a course on "big history" at Santa Cruz, in California. He persuaded me that the time had come to try to write a textbook on big history, in the hope that it might encourage others to teach similar courses. He has also given me invaluable (if sometimes painful) criticism on earlier drafts of this manuscript. And he has been a constant source of encouragement.

I am extremely grateful to all those who lectured or tutored in the big history course I taught at Macquarie University between 1989 and 1999. I list them in alphabetical order: David Allen, Michael Archer, Ian Bedford, Craig Benjamin, Jerry Bentley, David Briscoe, David Cahill, Geoff Cowling, Bill Edmonds, Brian Fegan, Dick Flood, Leighton Frappell, Annette Hamilton, Mervyn Hartwig, Ann Henderson-Sellers, Edwin Judge, Max Kelly, Bernard Knapp, John Koenig, Jim Kohen, Sam Lieu, David Malin, John Merson, Rod Miller, Nick Modjeska, Marc Norman, Bob Norton, Ron Paton, David Phillips, Chris Powell, Caroline Ralston, George Raudzens, Stephen Shortus, Alan Thorne, Terry Widders, and Michael Williams. I would also like to thank Macquarie University for the period of academic leave during which the first draft of this book was written.

Several people have been particularly supportive of the idea of big history, and some have taught other courses on the big history scale. John Mears started teaching such a class at about the same time as I did, and has always been an enthusiastic supporter of the idea. Tom Griffiths and colleagues taught a big history course at Monash University in the early 1990s. Johan Goudsblom began teaching one at the University of Amsterdam, and has been an enthusiastic supporter of the project. His colleague, Fred Spier, wrote the first book on big history, an ambitious and brilliantly argued case for the construction of a "grand unified theory" embracing the social sciences as well as the natural sciences *(The Structure of Big History: From the Big Bang until Today)*. Others who have expressed interest and support for such an approach or have taught similar courses include George Brooks, Edmund Burke III, Marc Cioc, Ann Curthoys, Graeme Davidson, Ross Dunn, Arturo Giráldez, Bill Leadbetter, and Heidi Roupp. At the American Historical Association conference in Seattle in January 1998, Arnold Schrier chaired a panel on big history that included papers from myself, John Mears, and Fred Spier, as well as a perceptive and supportive commentary from Patricia O'Neal. Gale Stokes invited me to discuss big history on a panel on "the play of scales" at the American Historical Association conference in San Francisco in January 2002.

A number of other people have read or commented on drafts of parts of this book. In addition to some of those already listed, they include Elizabeth Cobbs Hoffman, Ross Dunn, Patricia Fara, Ernie Grieshaber, Chris Lloyd, Winton Higgins, Peter Menzies, and Louis Schwartzkopf. Professor I. D. Koval'chenko invited me to give a talk on big history at Moscow University, and Valerii Nikolayev invited me to talk at the Institute of Oriental Studies in Moscow, both in 1990. Stephen Mennell asked me to speak about big history at a conference he convened almost ten years ago, and Eric Jones gave me invaluable feedback on that paper. Ken Pomeranz sent me a draft chapter from his then-unpublished book on the "great divergence" and in-

vited me to speak on big history at the University of California, Irvine. Over the years, I have given talks on big history at many other universities, including Macquarie and Monash Universities and the Universities of Sydney, Melbourne, Newcastle, Wollongong, and Western Australia in Australia; at the University of California, Santa Cruz; at Minnesota State University, Mankato; and at Indiana University, Bloomington, in the United States; at Victoria University in Canada; and at Newcastle and Manchester Universities in the United Kingdom. I worked with John Anderson for almost two years on a theoretical article on power- and wealth-maximizing societies. The article never saw the light of day, but collaborating with John gave me many new insights into the transition to modernity.

Since sending out copies of an earlier draft of this text in September 1999, I have received generous criticisms and comments from several other colleagues. They include (in alphabetical order): Alfred Crosby, Arturo Giráldez, Johan Goudsblom, Marnie Hughes-Warrington, William H. McNeill, John Mears, Fred Spier, and Mark Welter. I am also grateful to at least two anonymous reviewers recruited by the University of California Press. Marnie Hughes-Warrington taught with me in my big history course in 2000 and offered many invaluable suggestions. As a historiographer, she was able to alert me to historiographical implications of the subject that I had missed. William McNeill engaged in a long and generous correspondence with me about an earlier draft of this manuscript. His comments were both encouraging and critical, and they have shaped my own ideas substantially. In particular, he persuaded me to take more seriously the role of networks of exchange in world history.

I would also like to thank the many students whom I have taught at Macquarie in HIST112: An Introduction to World History, and at San Diego State University in HIST411: World History for Teachers and HIST100: World History. Their questions kept me focused on what is important. I am particularly thankful to those students who provided me with information or told me about new discoveries they found in books I didn't know about or on the Internet, and also to those who, by enjoying the course, made me feel it was worthwhile.

I feel I owe particular thanks to the staff of the University of California Press, including Lynne Withey, Suzanne Knott, and many others. Alice Falk copyedited my manuscript with terrifying thoroughness. Their professionalism, courtesy, and good humor greatly eased the complex and sometimes difficult passage from manuscript to book.

In a book on this scale, it goes without saying that no one I have thanked for their help or support is in any way to blame for errors in the text; nor

can it be assumed that any of them necessarily agree with the book's argument. I remained stubborn enough to resist many of the kindly criticisms that have been offered of its earlier drafts, so I must remain wholly responsible for all remaining errors of fact, interpretation, or balance.

I hope Chardi, Joshua, and Emily will think of this as a gift from me, a small return for the gift that they have been to me over many years.

David Christian
January 2003

PREFACE TO THE 2011 EDITION

Maps of Time was published in 2004. To my delight it was treated very kindly. I was surprised, because I expected historians in particular to reject the very idea of a sort of "universal history," a history of all of time. Skepticism there certainly was about the idea of big history, and plenty of quibbles about particular parts of the text, but most reviewers seemed convinced that the project was not absurd and could indeed yield interesting insights. Some were more enthusiastic, seeing big history as an exciting new area of historical scholarship. World historians were particularly generous in their support, a generosity reflected in the awarding to *Maps of Time* of the WHA prize for the best book in world history published in 2004. *Maps of Time* has also gone international, with translations into Spanish and Mandarin, which means it is now available in the world's three most widely spoken languages. A Korean translation is in preparation.

Since 2004, interest in big history has grown, and now big history can realistically be thought of as a rapidly emerging field of teaching and scholarship. Some idea of this boom can be gleaned from the bibliography compiled by Barry Rodrigue, Fred Spier, and Daniel Stasko and available from the International Big History Association web site at www.ibhanet.org. Recent works include a major survey of big history by Cynthia Brown, and Fred Spier's rich theorization of big history, *Big History and the Future of Humanity.*[1] In 2007 I recorded a set of lectures on big history published by the Teaching Company, and the college-level text in big history that I have written with Cynthia Brown and Craig Benjamin will be available in 2012.

I remain happy with the basic arguments of *Maps of Time,* though my own ideas have continued to evolve since 2004. Definitions of what big history is are acquiring a sharper focus. For example, it is clear that what distinguishes big history most decisively from world history is its interdisciplinary nature and its search for an underlying unity beneath the various accounts of the past told in different historically oriented disciplines. Big history studies the past across physics, astronomy, geology, biology, and human history. As it does so, it seeks common themes, paradigms, and methods, as well as a clearer understanding of differences in the subject matter, the methods, and the paradigms of different fields of historical scholarship.

Some ideas that were present but undeveloped in *Maps of Time* have since acquired sharper definition, both in my own mind and in the work of colleagues in the field. For example:

- In *Big History and the Future of Humanity,* Fred Spier has built on an earlier work of his and on the work of Eric Chaisson to produce what is currently by far the most sophisticated attempt to construct a thematic scaffolding for big history. He carefully links the idea of increasing complexity with the associated themes of energy flows and the idea of goldilocks conditions—the notion that complexity can increase only under very special conditions and within quite exacting "boundary conditions." Here are broad theoretical ideas that can help give greater depth and coherence to the story told within big history.
- I have explored the idea that the chronometric revolution—that is to say, the evolution of new ways of providing absolute dates for past events—was a crucial step toward big history.[2] Before the middle of the twentieth century (as H.G. Wells admitted ruefully in the 1920s), it was impossible to write a rigorous, scientific history of the entire universe, because absolute dates still had to be based on written texts, so they could reach back no further than a few thousand years. That may help explain the powerful convention that "history" really meant no more than the history of literate human societies. Only with the appearance of carbon 14 dating and related dating techniques in the 1950s did big history become possible.
- There has also been considerable discussion of the historiography of big history and of how the field fits into the evolution of historical thinking as a whole. My own attempt to think this through can be found in "The Return of Universal History."[3] Craig Benjamin has written a fine account of the evolution of big history in the introduction to a series of articles on the subject.[4]

One of the most exciting features of big history is its inherently global nature. Within big history, human beings are encountered first as a single species, and only very late in such a survey do national or civilizational perspectives acquire salience. As a result, big history holds out the prospect of creating a genuinely global account of the past of humanity, one not bound to national perspectives, an account that, like good science, should work as well in Seoul or Delhi or Buenos Aires as in London or New York.

New concepts are also emerging that capture well the distinctive perspective of big history. One of the most powerful is the idea proposed by the Nobel Prize–winning climatologist Paul Crutzen that today we have entered a new geological era, the "Anthropocene," the first era in the history of the planet in which a single species, our own, has become the dominant force in shaping the biosphere.[5] That vision of the contemporary world fits very well with big history's inherently ecological account of human history.

Since 2004 there have been major organizational developments in the field. The number of college-level courses in big history has increased rapidly, and there may be at least fifty such courses being taught throughout the world today. With the encouragement and support of Cynthia Brown, Dominican University of California in San Rafael (near San Francisco) has become the first university to introduce big history as a foundation course for first-year students. In April 2011, a scholarly organization was founded to develop big history as a research and teaching field: the International Big History Association. Barry Rodrigue and Daniel Stasko have traced the rapid expansion of teaching and scholarship in big history in essays available on the IBHA web site, and in August 2012 the IBHA will host the first major international big history conference in Michigan.[6] In March 2011 the "Big History Project" was launched to build a free online high school syllabus in big history.[7] There are many indirect signs that big history is finding its way to a wide audience. In Amsterdam, big history has been the subject of public debate for well over a decade, in response both to the University of Amsterdam's introduction of a big history course and to the granting to William McNeill of an Erasmus Prize in 1996. Fred Spier and Barry Rodrigue have tracked teachers and scholars interested in the field and have shown that a remarkable number of people are undertaking courses or research projects closely aligned with the goals of big history.

But despite these signs of growth, the field still has a long way to travel. The conventional borders between disciplines remain well policed and are sometimes defended with surprising aggression. This may help explain why, though there now exists a substantial body of big history scholarship, and big history promises to open up exciting new research agendas (including the meaning of complexity and energy flows, and the role of information across many disciplines), there are still no large interdisciplinary research projects in the field. At the time of writing, there is only one formal university appointment in big history (Fred Spier at the University of Amsterdam), and there exists only a tiny cohort of graduate students engaged in big history projects (three of them currently at Macquarie University in Sydney). A start has been made on teaching big history in high schools. But it remains to be seen how many schools and education departments will decide that teaching big history can help students understand the underlying unity and coherence of modern knowledge and appreciate the powerful intellectual synergies to be found in genuinely interdisciplinary thinking and teaching.

I am confident that big history will flourish, partly because it evidently has the ability, like a gestalt switch, to help students and scholars see familiar things in new ways. The other reason for my confidence is the energy, intelligence, generosity, and adventurousness of the small group of scholars who have helped build the field over the past two decades. Building big history has truly been an exercise in collective learning.

I would like to end by thanking William McNeill for lending his great authority to a field of historical scholarship that, even a decade ago, seemed extremely marginal. His support of big history has done a huge amount to persuade historians that the project is interesting, illuminating, and important, and that they may have much to gain by expanding their vision of what "history" means.

David Christian
Macquarie University
April 2011

NOTES

1. Cynthia Brown, *Big History: From the Big Bang to the Present* (New York: New Press, 2007); Fred Spier, *Big History and the Future of Humanity* (Malden, Mass., and Oxford: Wiley-Blackwell, 2010).

2. David Christian, "Historia, complejidad y revolución cronométrica" [History, complexity and the chronometric revolution], *Revista de Occidente* 323 (April 2008): 27–57; Christian, "The Evolutionary Epic and the Chronometric Revolution," in *The Evolutionary Epic: Science's Story and Humanity's Response*, ed. Cheryl Genet, Brian Swimme, Russell Genet, and Linda Palmer (Santa Margarita, Calif.: Collins Foundation Press, 2009), pp. 43–50; Christian, "History and Science after the Chronometric Revolution," in *Cosmos and Culture: Cultural Evolution in a Cosmic Context*, ed. Steven J. Dick and Mark L. Lupisella (Washington, D.C.: NASA, 2009), pp. 441–62.

3. David Christian, "The Return of Universal History," theme issue, *History and Theory* 49 (December 2010): 5–26.

4. Available at http://worldhistoryconnected.press.illinois.edu/6.3/index.html.

5. For short introductions, see David Christian, "The Anthropocene," *Berkshire Encyclopedia of World History*, 2nd ed. (Great Barrington, Mass.: Berkshire Publishing, 2010); and S. Will, P. J. Crutzen, and J. R. McNeill, "The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?," *Ambio* 36, no. 8 (December 2007): 614–21.

6. The web site of the IBHA can be found at www.ibhanet.org.

7. The "Big History Project" web site can be found at www.bighistoryproject.com.

INTRODUCTION

A MODERN CREATION MYTH?

"BIG HISTORY": LOOKING AT THE PAST ON ALL TIMESCALES

> [T]he way to study history is to view it as a long duration, as what I have called the *longue durée.* It is not the only way, but it is one which by itself can pose all the great problems of social structures, past and present. It is the only language binding history to the present, creating one indivisible whole.
>
> Universal history comprehends the past life of mankind, not in its particular relations and trends, but in its fullness and totality.
>
> A Moment's Halt—a momentary taste
> Of BEING from the Well amid the Waste—
> And Lo!—the phantom Caravan has reached
> The NOTHING it set out from—Oh, make haste!

Like merchants in a huge desert caravan, we need to know where we are going, where we have come from, and in whose company we are traveling. Modern science tells us that the caravan is vast and varied, and our fellow travelers include numerous exotic creatures, from quarks to galaxies. We also know a lot about where the journey started and where it is headed. In these ways, modern science can help us answer some of the deepest questions we can ask concerning our own existence, and that of the universe through which we travel. It can help us draw the line we all must draw between the personal and the universal.

"Who am I? Where do I belong? What is the totality of which I am a part?" In some form, all human communities have asked these questions. And in most human societies, educational systems, formal and informal, have tried to answer them. Often, the answers have been embedded in cycles of creation myths. By offering memorable and authoritative accounts of how everything began—from our own communities, to the animals, plants, and landscapes around us, to the earth, the Moon and skies, and even the universe itself—creation myths provide universal coordinates within which people can imagine their own existence and find a role in the larger scheme of things. Creation myths are powerful because they speak to our deep spiritual, psychic, and social need for a sense of place and a sense of belonging. Because they provide so fundamental a sense of orientation, they are often integrated into religious thinking at the deepest levels, as the Genesis story is within the Judeo-Christian-Islamic tradition. It is one of the many odd features of modern society that despite having access to more hard information than any earlier society, those in modern educational systems do not normally teach such a story. Instead, from schools to universities to research institutes, we teach about origins in disconnected fragments. We seem incapable of offering a unified account of how things came to be the way they are.

I have written this book in the belief that such intellectual modesty is unnecessary and harmful. It is unnecessary because the elements of a modern creation myth are all around us. It is harmful because it contributes to the subtle but pervasive quality of disorientation in modern life that the pioneering French sociologist Émile Durkheim referred to as "anomie": the sense of not fitting in, which is an inescapable condition of those who have no conception of what it is they are supposed to fit into.

Maps of Time attempts to assemble a coherent and accessible account of origins, a modern creation myth. It began as a series of lectures in an experimental history course taught at Macquarie University in Sydney. The idea of that course was to see if it was possible, even in the modern world, to tell a coherent story about the past on many different scales, beginning, literally, with the origins of the universe and ending in the present day. Each scale, I hoped, would add something new to the total picture and make it easier to understand all the other scales. Given the conventions of the modern history profession, this was an extremely presumptuous idea. But it turned out to be surprisingly doable, and even more interesting than I had originally supposed. Part of the task of my introduction will be to justify this distinctive way of thinking and teaching about the past.

I began teaching "big history" in 1989; two years later I published an essay in which I attempted a formal defense of this approach.[1] Though aware of the oddity of the project, those of us trying to teach big history were soon convinced that these large questions made for interesting classes and encouraged fruitful thinking about the nature of history. Teaching this large story persuaded us that beneath the awesome diversity and complexity of modern knowledge, there is an underlying unity and coherence, ensuring that different timescales really do have something to say to each other. Taken together, these stories have all the power and richness of a traditional cycle of creation myths. They constitute what indigenous Australians might call a modern "Dreaming"—a coherent account of how we were created and how we fit into the scheme of things.

We found something else that most premodern societies have known: there is an astonishing power to any story that attempts to grasp reality whole. This power is quite independent of the success or failure of any particular attempt; the project itself is powerful, and fulfills deep needs. Trying to look at the whole of the past is, it seems to me, like using a map of the world. No geographer would try to teach exclusively from street maps. Yet most historians teach about the past of particular nations, or even of agrarian civilizations, without ever asking what the *whole* of the past looks like. So what is the temporal equivalent of the world map? Is there a map of time that embraces the past at all scales?

This is a good moment to raise such questions, because there is a growing sense, across many scholarly disciplines, that we need to move beyond the fragmented account of reality that has dominated scholarship (and served it well) for a century. Scientists have moved fastest in this direction. The success of Stephen Hawking's *A Brief History of Time* (1988) also shows the great popular interest in trying to understand reality whole. In Hawking's own field, cosmology, the idea of a "grand unified theory" once seemed ridiculously overambitious. Now it is taken for granted. Biology and geology have also moved toward more unified accounts of their subject matter, with the consolidation, since the 1960s, of modern paradigms of evolution and plate tectonics.[2]

Scholars at the Santa Fe Institute in the United States have been exploring such interconnections for many years. An associate of the institute, the Nobel Prize–winning physicist Murray Gell-Mann, has eloquently stated the arguments for a more unified account of reality as they appear to a physicist.

> We live in an age of increasing specialization, and for good reason. Humanity keeps learning more about each field of study; and as every specialty grows, it tends to split into subspecialties. That process happens over and over again, and it is necessary and desirable. However, there is also a growing need for specialization to be supplemented by integration. The reason is that no complex, nonlinear system can be adequately described by dividing it up into subsystems or into various

> aspects, defined beforehand. If those subsystems or those aspects, all in strong interaction with one another, are studied separately, even with great care, the results, when put together, do not give a useful picture of the whole. In that sense, there is profound truth in the old adage, "The whole is more than the sum of its parts."
>
> People must therefore get away from the idea that serious work is restricted to beating to death a well-defined problem in a narrow discipline, while broadly integrative thinking is relegated to cocktail parties. In academic life, in bureaucracies, and elsewhere, the task of integration is insufficiently respected.

At the Santa Fe Institute, he adds, "People are found who have the courage to take a *crude look at the whole* in addition to studying the behavior of parts of a system in the traditional way."[3]

Should historians look for a similar unifying structure, perhaps a "grand unified story" that can summarize the best modern knowledge about origins from a historian's perspective? The rise of the new subdiscipline of world history is a sign that many historians also feel the need for a more coherent vision of their subject. Big history is a response to this need. In the late 1980s, John Mears, at Southern Methodist University (in Dallas, Texas), began teaching a history course on the largest possible scales at about the same time as I did. And since then, a number of other universities have offered similar courses—in Melbourne, Canberra, and Perth in Australia; in Amsterdam; and also in Santa Cruz in the United States. Fred Spier, from the University of Amsterdam, has gone one step further and written the first book on big history. In it, he offers an ambitious defense of the project of constructing a unified account of the past at all scales.[4]

Meanwhile, there is a growing sense among scholars in many fields that we may be close to a grand unification of knowledge. The biologist E. O. Wilson has argued that we need to start exploring the links between different domains of knowledge, from cosmology to ethics.[5] The world historian William McNeill has written:

> Human beings, it appears, do indeed belong in the universe and share its unstable, evolving character. . . . [W]hat happens among human beings and what happens among the stars looks to be part of a grand, evolving story featuring spontaneous emergence of complexity that generates new sorts of behavior at every level of organization from the minutest quarks and leptons to the galaxies, from long carbon chains to living organisms and the biosphere, and from the biosphere to the symbolic universes of meaning within which human beings live and labor, singly and in concert, trying always to get more of what we want and need from the world around us.[6]

I intend this book to contribute to the larger project of constructing a more unified vision of history and of knowledge in general. I am well aware of the difficulties of that project. But I am sure that it is both doable and important, so it is worth attempting in the hope that others may eventually do it better. I am also convinced that a modern creation myth will turn out to be as rich and as beautiful as the creation myths of all earlier communities; it is a story that deserves telling even if the telling is imperfect.

STRUCTURE AND ORGANIZATION

> utterly impossible as are all these events they are probably as like those which may have taken place as any others which never took person at all are ever likely to be
>
> If the Eiffel Tower were now representing the world's age, the skin of paint on the pinnacle-knob at its summit would represent man's share of that age; and anybody would perceive that that skin was what the tower was built for. I reckon they would, I dunno.

Erwin Schrödinger, one of the pioneers of quantum physics, described the difficulties of constructing a more unified vision of knowledge in the preface to a book he wrote on a biological topic—the origins of life. His preface also offers the best justification I know for presuming to undertake such a project.

> We have inherited from our forefathers the keen longing for unified, all-embracing knowledge. The very name given to the highest institutions of learning reminds us, that from antiquity and throughout many centuries the *universal* aspect has been the only one to be given full credit. But the spread, both in width and depth, of the multifarious branches of knowledge during the last hundred odd years has confronted us with a queer dilemma. We feel clearly that we are only now beginning to acquire reliable material for welding together the sum total of all that is known into a whole; but, on the other hand, it has become next to impossible for a single mind fully to command more than a small specialized portion of it.
>
> I can see no other escape from this dilemma (lest our true aim be lost forever) than that some of us should venture to embark on a synthesis of facts and theories, albeit with second-hand and incomplete knowledge of some of them—and at the risking of making fools of ourselves.
>
> So much for my apology.[7]

Some of the most daunting problems posed by big history are organizational. What shape will a modern creation myth take? From what standpoint should it be written? What objects will take center stage? What timescales will dominate?

A modern creation myth will not and cannot hope to be "neutral." Modern knowledge offers no omniscient "knower," no neutral observation point from which all objects, from quarks to humans to galaxies, have equal significance. We cannot be everywhere at once. So the very idea of knowledge from no particular point of view is senseless. (Technically, this statement reflects a philosophical position, associated with Nietzsche, known as *perspectivism.*) In any case, what use could such knowledge have? All knowledge arises from a relationship between a knower and an object of knowledge. And knowers expect to put knowledge to some use.

Creation stories, too, arise from a relationship between particular human communities and the universe as these communities imagine it. They offer answers to universal questions at many different scales, which is why they sometimes appear to have a nested structure similar to a Russian *matryoshka* doll—or to the Ptolemaic vision of the universe, with its many concentric shells. At the center are those trying to understand. At the outer edge is a totality of some kind: a universe or a deity. In between are entities that exist at different chronological, spatial, and mythic scales. It is thus the questions we ask that dictate the general shape of all creation myths. And because we are humans, humans are guaranteed to occupy more space in a creation myth than they do in the universe as a whole. A creation myth always belongs to *someone;* and the story recounted in this book is the creation myth of modern human beings, educated in the scientific traditions of the modern world. (Curiously, this means that the *narrative* structure of the modern creation myth, like all creation myths, may appear pre-Copernican, despite its definitely *post*-Copernican content.)

Though its scope is vast, *Maps of Time* aims at not overwhelming the reader with detail. I have tried (without complete success) to stop the book from growing too large, in the hope that the details will not obscure the larger picture. Those with a particular interest in any one part of this story will have no difficulty finding out more, and the brief guides to further reading at the end of each chapter provide some starting points.

The exact balance of topics and themes in this book reflects the fact that this is an attempt at big history from a historian's perspective, not that of an astronomer, a geologist, or a biologist. (Some alternative approaches to big history are listed at the end of this introduction.) This means that human societies loom larger than they do in, for example, Stephen Hawking's books, or in Preston Cloud's *Cosmos, Earth, and Man* (1978). Nevertheless, the first five chapters cover topics that normally fall within the sciences of cosmology, geology, and biology. They discuss the origins and evolution of the universe, of galaxies and stars, of the solar system and the earth, and of life on earth. The rest of the book surveys the history of our own species and its relationship to the earth and to other species. Chapters 6 and 7 discuss the origins of human beings and the nature of the earliest human societies. They attempt to identify what is distinctive about human history, and what distinguishes humans from other organisms inhabiting this earth. Chapter 8 examines the earliest agrarian societies, which existed without cities or states. With the emergence of agriculture, about 10,000 years ago, humans began for the first time to live in dense communities, in which exchanges of information and goods became more intensive than ever before. Chapters 9 and 10 describe the emergence and evolution of cities, of states, and of agrarian civilizations. Chapters 11 to 14 try to construct a coherent interpretation of the modern world and its origins. Finally, chapter 15 looks to the future. Big history is inevitably concerned with large trends, and these do not stop suddenly in the present moment. So a large view of the past inevitably raises questions about the future, and at least some answers are available, both for the near future (say, the next 100 years), and the remote future (the next few billion years). Raising such questions should be a vital part of modern education, for our assessments of the future will affect decisions taken today; these, in turn, may shape the world inhabited by our own children and grandchildren. They will not thank us if we take such tasks lightly.

A second organizational difficulty is thematic. It may seem there can be little coherence in a narrative that spans so many different scholarly disciplines. But there are phenomena that cross all scales. Above all, it turns out that the main actors are similar. At every level, we will be interested in ordered entities, from molecules to microbes to human societies to large chains of galaxies. Explaining how such things can exist, how they are born, how they evolve, and how, eventually, they perish is the stuff of history at all scales. Of course, each scale also has its own rules—chemical in the case of molecules, biological in the case of microbes—but the surprise is that some underlying principles of change may be universal. This is why Fred Spier has argued that at a fundamental level, big history is about "regimes." It is about the fragile ordered patterns that appear at all scales, and the ways in which they change.[8] So a central theme of big history is how the rules of change vary at different scales, despite some fundamental similarities in the nature of all change. Human history *is* different from cosmological history; but it is not *totally* different. I discuss some of the general principles of change in appendix 2, but the book as a whole will explore some of the different rules of change that appear at different scales.

FOR AND AGAINST BIG HISTORY

Specialists in many fields, from geology to archaeology and prehistory, will find it quite natural to look at the past on very large scales. But not everyone will be persuaded that big history is worth doing. Particularly to professional historians, the idea of exploring the past on such huge timescales can seem overambitious and perhaps simply impossible, a diversion from the real tasks of historical scholarship. In the last part of this introduction, I will respond to four main reservations that I have encountered.

The first is common, particularly among professional historians. It is that on large scales, history must thin out. It must lose detail, texture, particularity, and substance. Eventually, it must become vacuous. To be sure, on large scales, themes and problems familiar to professional historians may vanish, just as the details of a familiar landscape may disappear as one looks down from an airplane as it climbs. In a big history course, the French Revolution may get no more than a passing mention. But there are compensations. As the frame through which we view the past widens, features of the historical landscape that were once too large to fit in can be seen whole. We can begin to see the continents and oceans of the past, as well as the villages and roadways of national and regional histories. Frames of any kind exclude more than they reveal. And this is particularly true of the conventional time frames of modern historiography, which normally extend from a few years to a few centuries. Perhaps the most astonishing thing the conventional frames hide is humanity itself. Even on time frames of several thousand years, it is difficult to ask questions about the broader significance of human history within an evolving biosphere. Yet in a world with nuclear weapons and ecological problems that cross all national borders, we desperately need to see humanity as a whole. Accounts of the past that focus primarily on the divisions between nations, religions, and cultures are beginning to look parochial and anachronistic—even dangerous. So, it is not true that history becomes vacuous at large scales. Familiar objects may vanish, but new and important objects and problems come into view. And their presence can only enrich the discipline.

A second possible objection is that to write big history, historians will have to move beyond the boundaries of the discipline. Of course, this is true. Synoptic studies like this book are risky because the author depends on secondary sources and on *other* synoptic studies. As a result, there will inevitably be blunders and misunderstandings: error is built into the project. Indeed, it is part of the process of learning. To understand your own country, you must travel beyond its borders at least once in your life. You will not understand everything you see; but you may begin to see your own country in a new light. The same is true of history. To understand what is distinctive about human history, we must have some idea of how a biologist or a geologist might approach the subject. We cannot *become* biologists or geologists, and our understanding of these fields will have its limits; but we do have to use as skillfully as we can the expertise of specialists in other fields. And we have much to learn from their different perspectives on the past. Excessive respect for disciplinary boundaries has hidden many possibilities for intellectual synergy between disciplines. I will argue, for example, that we need the vision of a biologist to see what is truly distinctive about our type of animal, *Homo sapiens.*

Third, it may be objected that big history proposes to create a new "grand narrative" just when we have learned the futility, even the danger, of grand narratives. Will not a big history metanarrative crowd out alternative histories—of minorities, of regions, of particular nations or ethnic groups?[9] Perhaps a fragmented vision of the past (a "jeweler's-eye" view, in the phrase used by the anthropologists George Marcus and Michael Fischer) is the only one that can do real justice to the richness of human experience.[10] Natalie Zemon Davis makes the point well:

> The question remains whether a single master narrative is an adequate goal for global history. I think not. Master narratives are especially vulnerable to be taken over by patterns characteristic of the historian's time and place, however useful they may be for accounting for some of the historical evidence. If a new decentred global history is discovering important alternative historical paths and trajectories, then it might also do well to let its big stories be alternate or multiple. The challenge for global history is to place these narratives creatively within an interactive frame.[11]

Once again, the charge is at least partly true. Narratives of some kind seem unavoidable when looking at the past on large scales, and they will certainly be shaped by contemporary concerns. Nevertheless, it is a mistake for historians to shun these large narratives, however grand they may seem. Like it or not, people will look for, and find, large stories, because they can provide a sense of meaning. As William Cronon has written of environmental history: "When we describe human activities within an ecosystem, we seem always to tell *stories* about them. Like all historians, we configure the events of the past into causal sequences—stories—that order and simplify those events to give them new meanings. We do so because narrative is the chief literary form that tries to find meaning in an overwhelmingly crowded and disordered chronological reality."[12] If paid intellectuals are too finicky to shape these stories, they will flourish all the same; but the intellectuals will be ignored and will eventually disenfranchise themselves. This is an abdication of responsibility, particularly as intellectuals have played such a crucial role in creating many of today's metanarratives. Metanarratives exist, they are powerful, and they are potent. We may be able to domesticate them; but we will never eradicate them. Besides, while grand narratives are powerful, subliminal grand narratives can be even more powerful. Yet a "modern creation myth" already exists just below the surface of modern knowledge. It exists in the dangerous form of poorly articulated and poorly understood fragments of modern knowledge that have undermined traditional accounts of reality without being integrated into a new vision of reality. Only when a modern creation myth has been teased out into a coherent story will it really be possible to take the next step: of criticizing it, deconstructing it, and perhaps improving it. In history as in building, construction must precede deconstruction. We must see the modern creation myth before we can criticize it. And we must articulate it before we can see it. Ernest Gellner made this point well in the introduction to his attempt at a synoptic view of history, *Plough, Sword, and Book* (1991):

> The aim of the present volume is simple. It is to spell out, in the sharpest and perhaps exaggerated outline, a vision of human history which has been assuming shape of late, but which has not yet been properly codified. The attempt to bring it to the surface is not made because the author has any illusions about *knowing* it to be true: he does not. Definitive and final truth is not granted to theories in general. In particular, it is unlikely to attach to theories covering an infinite diversity of extremely complex facts, well beyond the reach of any one scholar. The vision is formulated in the hope that its clear and forceful statement will make possible its critical examination.[13]

Besides, a "grand narrative" of the kind offered in this book may prove surprisingly capacious. In the global "truth" market of the twenty-first century, all narratives face stiff competition. The many detailed stories of the past already taught in our schools and universities ensure that a modern creation myth will emerge not as a single monolithic story but rather as a large and ramshackle cycle of stories, each of which can be told in many ways and with many variants. Indeed, it may turn out that the very large narratives create more space for alternative accounts of the past that struggle to survive within existing (and less ample) history syllabi. As Patrick O'Brien has written, "Hopefully as more historians risk writing on a global scale, the field will achieve a reputation and produce competing metanarratives to which the overwhelming flow of parish, regional and national histories could be reconnected."[14]

The fourth objection is closely related to the third: is not a narrative on this huge scale bound to make exaggerated truth claims? I have found in teaching big history that students struggle to find a balance between two extreme positions. On the one hand, they are tempted to suppose that a modern, "scientific" account of origins is true, while all earlier accounts were more or less false. On the other hand, faced with some of the uncertainties of modern accounts of the past, they may be tempted to think that this is "just one more story."

Thinking of a big history narrative as a modern creation myth is a good way of helping students to find the epistemological point of balance between these extremes. For it is a reminder, first, that *all* accounts of reality are provisional. Many of the stories we tell today will seem quaint and childish in a few centuries, just as many elements of traditional creation myths seem naive today. But by acknowledging this, we do not commit ourselves to a nihilistic relativism. All knowledge systems, from modern science to those embedded in the most ancient of creation myths, can be thought of as maps of reality. They are never just true or false. Perfect descriptions of reality are unattainable, unnecessary, and too costly for learning organisms, including humans. But workable descriptions are indispensable. So knowledge systems, like maps, are a complex blend of realism, flexibility, usefulness, and inspiration. They must offer a description of reality that conforms in some degree to commonsense experience. But that description must also be useful. It must help solve the problems that need to be solved by each community, whether these be spiritual, psychological, political, or mechanical.[15]

In their day, all creation myths offered workable maps of reality, and that is why they were believed. They made sense of what people knew. They contained much good, empirical knowledge; and their large structures helped people place themselves within a wider reality. But each map had to build on the knowledge and fulfill the needs of a particular society. And that is why they don't necessarily count as "true" outside their home environments. A modern creation myth need not apologize for being equally parochial. It must start with modern knowledge and modern questions, because it is designed for people who live in the modern world. We need to try to understand our universe even if we can be certain that our attempts can never fully succeed. So, the strongest claim we can make about the truth of a modern creation myth is that it offers a unified account of origins *from the perspective of the early twenty-first century.*

FURTHER READING ON BIG HISTORY

Listed below are a number of works in English that explore the past on scales larger than those of world history, or try to see human history in its wider context, or provide methodological frameworks for such attempts. This is a wide definition of "big history," and there are doubtless many other works that could be included under it. The authors come from many different fields, and the books vary greatly in approach and quality, so there is plenty of room for argument as to which do and which do not really count as big history books. This preliminary bibliography is based on a list first compiled by Fred Spier. It excludes books so technical that they cannot possibly be of use to historians or general readers. It also excludes a vast number of books that operate at large scales, and have much to offer historians, but do not try to move across multiple timescales.

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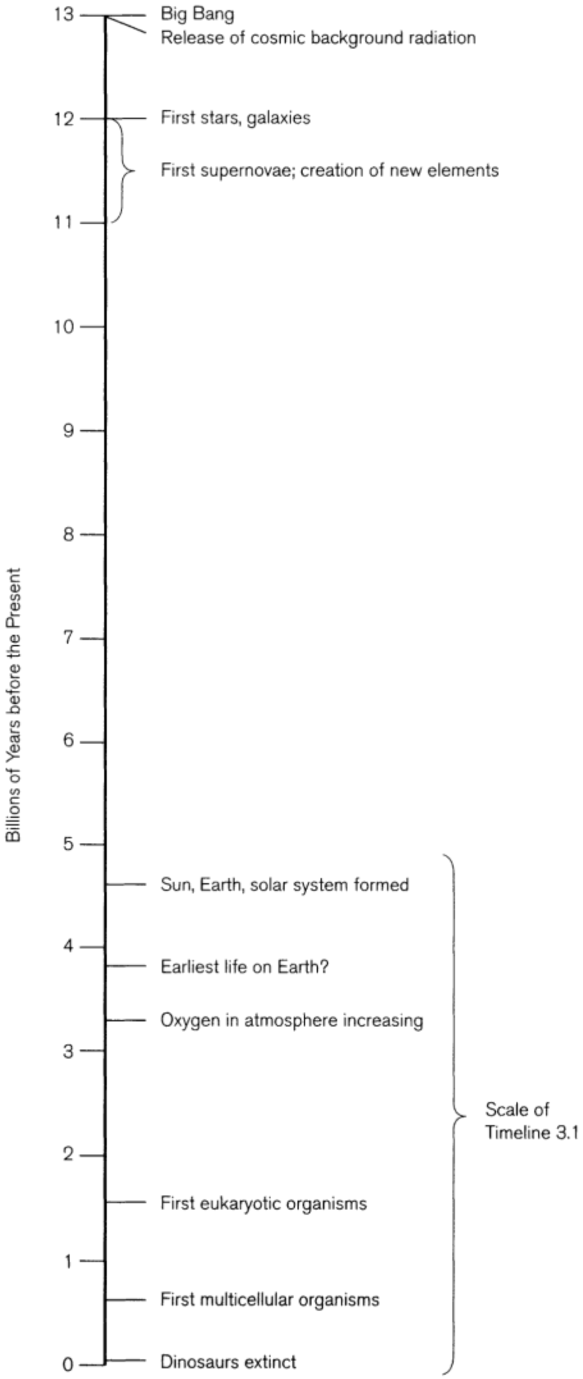
PART I

THE INANIMATE UNIVERSE



Timeline 1.1. The scale of the cosmos: 13 billion years.

1

THE FIRST 300,000 YEARS

ORIGINS OF THE UNIVERSE, TIME, AND SPACE

Viola: What country, friends, is this?
Captain: This is Illyria, lady.

THE PROBLEM OF BEGINNINGS

How did everything begin? This is the first question faced by any creation myth and, despite the achievements of modern cosmology, answering it remains tricky.

At the very beginning, all explanations face the same problem: how can something come out of nothing? The problem is general, for beginnings are inexplicable. At the smallest scales, subatomic particles sometimes emerge instantaneously from nothingness. One moment there is nothing; the next moment there is something. There is no in-between state. Quantum physics can analyze these odd jumps into and out of existence with great precision, but it cannot explain them in ways that make sense at the human level. These paradoxes are captured beautifully in a modern Australian Aboriginal saying: "Nothing is nothing."[1]

Awareness of the difficulty of explaining origins is as old as myth. The following passage poses these questions with great sophistication and a surprisingly modern skepticism. It comes from one of the ancient Indian hymns known as the Rig-Veda, and was probably composed ca. 1200 BCE. It describes a pre-creation realm that was not really present, but was not entirely absent either.

> There was neither non-existence nor existence then; there was neither
> the realm of space nor the sky which is beyond. What stirred?
> Where? In whose protection? Was there water, bottomlessly deep?
> There was neither death nor immortality then. There was no distinguishing sign of night nor of day. That one breathed, windless,
> by its own impulse. Other than that there was nothing beyond. . . .

> Was there below? Was there above? There were seed-placers; there were
> powers. There was impulse beneath; there was giving-forth above.
> Who really knows? Who will here proclaim it? Whence was it produced?
> Whence is this creation? The gods came afterwards, with the creation
> of this universe. Who then knows whence it has arisen?
> Whence this creation has arisen—perhaps it formed itself, or perhaps it
> did not—the one who looks down on it, in the highest heaven, only
> he knows—or perhaps he does not know.[2]

Here we have a hint that there was, first, a sort of potent nothingness—waiting, like clay in a potter's yard, to be formed into something. This is very much how modern nuclear physics views the idea of a vacuum: it is empty but can nevertheless have shape and structure, and (as has been proved in experiments with particle accelerators) "things" and "energies" can pop out of the emptiness.

Perhaps there was a potter (or potters) waiting to shape the vacuum. And perhaps the potter and the clay were somehow identical. According to the *Popol Vuh*, or "Council Book," a sixteenth-century Mayan manuscript, "Whatever might be is simply not there: only murmurs, ripples, in the dark, in the night. Only the Maker, Modeler alone, Sovereign Plumed Serpent, the Bearers, Begetters are in the water, a glittering light. They are there, they are enclosed in quetzal feathers, in blue-green."[3] But where did the Maker come from? Each beginning seems to presuppose an earlier beginning. In monotheistic religions, such as Christianity or Islam, the problem arises as soon as you ask, How was God created? Instead of meeting a single starting point, we encounter an infinity of them, each of which poses the same problem.

There are no entirely satisfactory solutions to this dilemma. What we have to find is not a solution but some way of dealing with the mystery, some way of "pointing at the moon," in the Zen metaphor. And we have to do so using words. Yet the words we reach for, from *God* to *gravity*, are inadequate to the task. So we have to use language poetically or symbolically; and such language, whether used by a scientist, a poet, or a shaman, can easily be misunderstood. A French anthropologist, Marcel Griaule, once questioned a Dogon wise man, Ogotemmeli, about a mythic detail according to which many animals were crowded together onto a single, small step (like the animals in Noah's ark). Ogotemmeli replied, with some irritation: "All of this has to be said in words, but everything on the step is a symbol. . . . Any number of symbols could find room on a one-cubit step." The word translated here as "symbol" could also be translated as "word of this lower world."[4] At the very beginning of things, language itself threatens to break down.

One of the trickiest problems concerns time. Was there a "time" when there was no time? Is time a product of our imagination?[5] In some systems of thought, time does not really exist. Places become the source of everything significant, and the paradoxes of creation take different forms.[6] But for communities that see time as central, there is no way of avoiding the paradox of origins. The following is an Islamic summary of a Zoroastrian attempt to deal with these riddles. In it, the creator is an unchanging entity called Time, who creates a universe of change. It is dominated by two opposite principles, those of the gods Ohrmazd and Ahriman.

> Except Time all other things are created. Time is the creator; and Time has no limit, neither top nor bottom. It has always been and shall be for evermore. No sensible person will say whence Time has come. In spite of all the grandeur that surrounded it, there was no one to call it creator; for it had not brought forth creation. Then it created fire and water; and when it had brought them together, Ohrmazd came into existence, and simultaneously Time became Creator and Lord with regard to the creation it had brought forth. Ohrmazd was bright, pure, sweet-smelling, and beneficent, and had power over all good things. Then, he looked down, he saw Ahriman ninety-six thousand parasangs away, black, foul, stinking, and maleficent; and it appeared fearful to Ohrmazd, for he was a frightful enemy. And when Ohrmazd saw this enemy, he thought thus: "I must utterly destroy this enemy," and he considered with what and how many instruments he could destroy him. Then did Ohrmazd begin the work of creation. Whatever Ohrmazd did, he did with the aid of Time; for all the excellence that Ohrmazd needed, had (already) been created.[7]

Time, like pattern, means difference, if no more than the difference between then and now. So this story, like most creation stories, is really about the emergence of difference from an original sameness. In this version, as in many creation myths, difference begins with a fundamental clash of opposites.

One of the more poetic solutions to these paradoxes is to think of creation as a sort of awakening. A story from the Karraru people of southern Australia describes how, originally, the earth was still, silent, and dark. However, "Inside a deep cave below the Nullarbor Plain slept a beautiful woman, the Sun. The Great Father Spirit gently woke her and told her to emerge from her cave and stir the universe into life. The Sun Mother opened her eyes and darkness disappeared as her rays spread over the land; she took a breath and the atmosphere changed, the air gently vibrated as a small breeze blew." The Sun Mother then goes on a long journey during which her rays awaken all the various creatures and plants that have been sleeping.[8] Such a story suggests that creation is not a single event but has to be constantly repeated; and, as we will see, this is a truth we all experience. The paradoxes of creation are repeated each time we observe something new, from galaxies to stars to solar systems and life. And many of us also experience our own personal origins, the moments of our earliest memories, as a sort of awakening from nothingness.

Modern science has approached the problem of origins in many different ways, some more satisfying than others. In *A Brief History of Time* (1988), Stephen Hawking suggests that the question of origins is just badly posed. If we think of time as a line, it is natural to ask about its beginning. But what if the universe has a different shape? Perhaps time is more like a circle. There is no sense in asking if a circle has a beginning or an end, just as there is no point in asking what is to the north of the North Pole. There is no beyond, no boundary, and everything about the universe is perfectly self-contained. As Hawking puts it: "The boundary condition of the universe is that it has no boundary."[9] Many creation myths adopt a similar approach, perhaps because they arise in societies that do not think of time as a straight line. As we look back in time, the past seems to fade away into what modern Aboriginal myths call a "Dreamtime." It is as if the past turned a corner beyond which we cannot see it anymore, however hard we try. The same is true if we look forward, so it seems as if in some sense the future and the past may meet.[10] Mircea Eliade describes similar visions of time in a difficult but fascinating work, *The Myth of the Eternal Return* (1954).[11]

In modern societies, which usually envisage time as a line rather than a curve, such solutions may seem artificial. Perhaps, instead, the universe is eternal. We can look back along the line of time as long as we like, but we will always find a universe, so the problem of origins does not really arise. Religions of the Indian subcontinent, in particular, have tended to adopt this strategy. So has the steady state theory, the most serious modern alternative to big bang cosmology. And so does a recent theory, proposed by Lee Smolin, that suggests the existence of universes that breed other universes whenever they create black holes, in a repetitive or "algorithmic" process analogous to Darwinian evolution, which ensures that they "evolve" in ways that increase the possibility of creating complex entities such as ourselves (see chapter 2).[12] Similar arguments are common in modern cosmology, and what they imply is that the universe we see may be merely one tiny atom in a much larger "multiverse." But such approaches are also unsatisfying, because they still leave the nagging question, How did such eternal processes themselves begin? How was an eternal universe created?

Or we can return to the idea of a creator. Within Christianity, it was generally agreed that the Creator made the universe a few thousand years ago.

In one famous calculation, a Dr. Lightfoot from Cambridge "proved" that God had created humans at exactly 9:00 AM on 23 October 4004 BCE.[13] Many other creation myths also introduce deities who created the world, working like potters, or builders, or clockmakers. This approach solves much of the problem, but leaves open the basic question of how the gods themselves were created. Once again, we seem forced back to an infinite regress.

A final position is skepticism. This entails a frank admission that at a certain point, we must run out of knowledge. Human knowledge, by its nature, has limits, so some questions must remain mysteries. Some religions treat such mysteries as secrets that the gods choose to hide from humans; others, such as Buddhism, treat them as ultimate riddles that are not worth pursuing. We will see that modern cosmology also opts for skepticism at the beginning of its story, though it offers a very confident account of how our universe evolved once it was created.

EARLY SCIENTIFIC ACCOUNTS OF THE UNIVERSE

Modern science tries to answer questions about origins using carefully tested data and rigorous logic. Though many pioneering scientists, like Newton, were Christians who believed deeply in the existence of a deity, they also felt the Deity was rational, so their task was to tease out the underlying laws by which the Deity had created the world. This meant trying to explain the world *as if there were no deity.* Modern science, unlike most other traditions of knowledge, tries to explain the universe as if it were inanimate, as if things happened without intention or purpose.

The Christian view of the universe owed much to the ideas of the Greek philosopher Aristotle. Though some Greeks had argued that the earth orbited the Sun, Aristotle placed the earth at the center of the universe and surrounded it with a series of transparent spheres, each revolving at a different speed. The spheres held the planets, the Sun, and the stars. This model sounds quaint today, but it was given a rigorous mathematical basis by Ptolemy in the second century CE, and in this form it proved good at predicting planetary motions. Christianity added the further idea that this universe had been created perhaps 6,000 years ago by God, in the course of five days. In sixteenth- and seventeenth-century Europe, the Ptolemaic story began to break down. Copernicus gave some powerful reasons for thinking that the earth revolved around the Sun, and the heretical monk Giordano Bruno argued that stars were suns and that the universe was probably infinite in extent. In the seventeenth century, scientists such as Newton and Galileo explored many of the implications of these ideas, while retaining as much as they could of the biblical creation story.

During the eighteenth century, the Ptolemaic view of the universe finally collapsed. In its place, there emerged a new picture of a universe operating according to strict, rational, and impersonal laws that could, in principle, be discovered by science. God may have created it, perhaps in time; perhaps, in some sense, out of time. But then he left it to run almost entirely according to its own logic and rules. Newton assumed that both time and space were absolutes, providing the ultimate frames of reference for the universe. It was widely accepted that both might be infinite, and thus the universe had neither a definable edge nor a time of origin. In this way, God was moved further and further away from the story of origins.

But there were problems. One arose from the theory of thermodynamics, which suggested that the amount of usable energy in the universe was constantly diminishing (or that entropy was constantly increasing; see appendix 2). In an infinitely old universe the consequence would be that no usable energy was left to create anything—yet clearly that was not true. Perhaps, this might have suggested, the universe was not infinitely old. The night sky posed another problem. As early as 1610, the astronomer Johannes Kepler pointed out that if there were an infinite number of stars, the night sky should be infinitely bright. The problem is now known as *Olber's paradox,* after a nineteenth-century German astronomer who publicized the problem more widely. One possible solution was to suppose that the universe was not infinitely large. That would solve Olber's paradox—but would create another; for as Newton had pointed out, if the universe were *not* infinitely large, then gravity ought to draw all the matter into the center of the universe, like oil in a sump. And that, fortunately, was not what astronomers observed when they studied the night sky.

Of course, all scientific theories contain problems. But as long as the theories can answer most of the questions put to them, such difficulties can be ignored. And the problems faced by the Newtonian theory were largely ignored in the nineteenth century.

THE BIG BANG: FROM PRIMORDIAL CHAOS TO THE FIRST SIGNS OF ORDER

In the first half of the twentieth century, evidence began to accumulate for an alternative theory that we now know as *big bang cosmology.* It solved the problem of entropy by suggesting the universe was not infinitely old; it solved Olber's paradox by describing a universe that was finite in both time and space; and it solved the paradox of gravity by showing that the universe was expanding too fast for gravity to gather everything into a single lump (yet!). Big bang cosmology described a universe with a beginning and a history, so it turned cosmology into a historical science, an account of change and evolution.

According to this view, the universe began as an infinitesimally small entity, which expanded rapidly and continues to expand today. In form, at least, this account is similar to the traditional creation myths known as *emergence myths.* In such accounts, the universe develops, like an egg or an embryo, through distinct stages from a remote and perhaps undefinable point of origin, and under the control of internal laws of development. In 1927, one of the pioneers of big bang cosmology, Georges Lemaître, referred to the early universe as the "primordial atom." Like all emergence myths, the modern account implies that the universe was created at a particular time, that it has a life story of its own, and that it may die in the distant future. The new theory could explain many of the difficulties encountered by previous theories. For example, it could explain Olber's paradox by showing that the universe had not existed forever; and because light has a finite speed (as Einstein had shown), light from the most distant galaxies might not reach us during the entire life of the universe. The theory was also consistent with the torrent of new information and data about stars, matter, and energy that was generated in the early twentieth century. But at its very beginning, it too has to fall back on a sense of inexplicable mystery.

The modern story of origins goes something like this.[14] The universe was created about 13 billion (13,000,000,000) years ago.[15] (How long ago is that? If each human being were to live exactly the biblical span of 70 years, it would take about 200 million human life spans laid end to end to reach back this far in time. For more on these huge timescales, see appendix 1.) About the beginning, we can say nothing with any certainty except that something appeared. We do not know why or how it appeared. We cannot say whether anything existed before. We cannot even say that there was a "before" or a "space" for anything to exist in, for (in an argument anticipated by St. Augustine in the fifth century CE) time and space may have been created at the same time as matter and energy. So, we can say nothing definite about the moment of the big bang, or about any earlier period.

However, beginning a tiny fraction of a second after the big bang, modern science can offer a rigorous and coherent story, based on abundant evidence. Many of the most interesting "events" occurred within a fraction of a second. Indeed, it may be helpful to think of time itself as stretched out during these early moments, so that a billionth of a billionth of a second then was as significant, in its way, as many billions of years in the later history of the universe.[16]

In the beginning, the universe was tiny, perhaps smaller than an atom. (How small is that? The physicist Richard Feynman illustrated the size of an atom by saying that if you blew up an apple until it was the size of Earth, each of the atoms it was made from would now be the size of the original apple.)[17] The temperature of this atom-sized universe was many trillions of degrees. At this temperature, matter and energy are interchangeable—as Einstein showed, matter is really little more than a congealed form of energy. Here, in this fantastically dense flux of energy/matter, we come close to the primordial chaos of so many traditional creation myths. But in the modern account, this tiny universe was expanding at a staggering speed, and it was this expansion that gave rise to the first differences and the first patterns.[18] The theory of inflation asserts that for a fraction of a second, between ca. 10^{-34} and 10^{-32} seconds after the big bang, the universe expanded faster than the speed of light (which is about 300,000 kilometers per second), driven apart by some form of "antigravity." The magnitudes involved in such processes are inconceivable: before inflation, the entire universe may have been smaller than an atom; after inflation (a fraction of an instant later), it may have been larger than a galaxy. Inflation seems to ensure that most of the universe is beyond our observation, as light from most of the universe will be too distant ever to reach us. The parts of the universe we can see may be only a tiny part of the real universe. As Timothy Ferris puts it: "If the entirety of an inflationary universe were the surface of the earth, the observable part would be smaller than a proton."[19]

As the universe expanded, it became less homogenous. Its original symmetry was broken, distinct patterns appeared, and matter and energy began to assume forms that we can recognize today. Modern nuclear physics can tell at what temperatures particular types of energy or matter appear, just as most of us can tell at what temperature water will turn into ice. So, if we can estimate how fast the universe cooled, then we can estimate when different forces and particles emerged from the flux of the early universe. Within the first second, quarks appeared, and from these were constructed protons and neutrons, the main constituents of atomic nuclei. Quarks and atomic nuclei are held together by the strong nuclear force, one of the four fundamental forces that rule our universe.

At this point in the modern creation story (still less than $\frac{1}{1000}$ of a second after the big bang), there occurs a display of extravagance that is remarkable even by the extravagant standards of most creation myths. Particles appeared in two forms, to make up almost equal amounts of matter and antimatter. Particles of antimatter are identical to particles of matter except for having the opposite electrical charge. Unfortunately, when the two meet, they annihilate each other and 100 percent of their mass is transformed into energy. So, during the first second after the big bang there played out a perverse subatomic game of musical chairs, in which quarks were the players, antiquarks were the chairs, and the winner was the one quark in a billion that couldn't find an antiparticle chair. The matter left to construct our universe was made from the one in a billion particles that didn't find an antimatter partner. The particles that *did* find a partner were transformed into pure energy, and that energy pervades the universe today, in the form of cosmic background radiation.[20] And this process may explain why there are about a billion photons of energy for every particle of matter in the universe today.

Now the pace slows. Some seconds after the big bang, electrons appeared. Electrons carry a negative electrical charge, while protons (which are made up of quarks) carry a positive charge. Relations between electrons and protons were controlled by a second fundamental force, the electromagnetic force, which also appeared within the first second of the universe's history. In the hot early universe, the photons of energy that carry the electromagnetic force were entangled with charged particles of matter. The universe was rather like the interior of the Sun today: a white-hot sea of particles and photons in constant interaction. The entire universe would have been crackling with the energy generated by constant interactions between positive protons and negative electrons and light. In this "era of radiation," as Eric Chaisson explains, matter existed as no more than "a relatively thin microscopic precipitate suspended in a macroscopic, glowing 'fog' of dense, brilliant radiation."[21]

After perhaps 300,000 years, the average temperature of the universe fell to ca. 4,000°C above absolute zero, and this cooling made possible one of the most fundamental of all transitions in the history of the universe.[22] Moments of transition are as mysterious as beginnings, and they will occur throughout our story. One of the most familiar examples in daily life is the transition that takes place when water turns into steam. Water is heated, and for a time all that seems to happen is that it gets warmer. Change occurs gradually, and we can watch it happening. Then, abruptly, a threshold is crossed; something new is created and the whole system enters a new phase. What had been liquid becomes gas. Why should a threshold occur at this particular point, in this case at 100°C (at sea level)? Sometimes we can explain transitions from one state to another, and the answer generally turns on a changing balance between different forces—between gravity, pressure, heat, electromagnetic forces, and so on. Sometimes we simply do not know why a threshold is crossed at a particular point.

The ending of the radiation era is a transition that physicists can more or less explain as a result of a balance between the falling energy of light photons as the universe expanded and the electromagnetic forces acting at the subatomic level. As the universe expanded, it cooled, and the energy of the light flowing through it fell sufficiently to enable positive protons to capture negative electrons and create stable, and thus electrically neutral, atoms. Because of that neutrality, atoms no longer interacted strongly with photons (though subtle interactions could still occur). As a result, photons of light could now flow freely through the universe. For most purposes, matter and energy ceased to interact. They became separate realms, like matter and spirit in the cosmologies of the Judeo-Christian-Islamic world. The era after this decoupling can be described as the "era of matter."[23]

The first atoms were extremely simple. Most were hydrogen atoms, consisting of one proton and one electron. But there also appeared about one-third as many helium atoms, each with two protons and two electrons, as well as a trace of even larger atoms. All atoms are tiny, with diameters of roughly one-ten-millionth of a centimeter. But they consist mostly of empty space. The protons and neutrons huddle together in the nucleus, while the electrons orbit far away from them. As Richard Feynman puts it: "If we had an atom and wished to see the nucleus we would have to magnify it until the whole atom was the size of a large room, and then the nucleus would be a bare speck which you could just about make out with the eye, but almost *all the weight* of the atom is in that infinitesimal *nucleus.*"[24] Three hundred thousand years after its creation, the universe was still simple. It consisted mostly of empty space, within which there drifted huge clouds of hydrogen and helium, and through which there poured an immense amount of energy.

Table 1.1 is a brief chronology of the early history of the universe. About 300,000 years after the big bang, all the ingredients of creation were present: time, space, energy, and the basic particles of the material universe, including protons, electrons, and neutrons, now mostly organized into atoms of hydrogen and helium. Since that time, nothing has really changed. The same energy and the same matter have continued to exist. All that has happened is that for the next 13 billion years these same ingredients have arranged themselves in different patterns, which constantly form and dissipate. From one perspective, the rest of the modern creation myth is merely the story of these different patterns.

But for us the patterns are all-important because we are pattern-detecting organisms. The patterns that emerged include the galaxies and stars, the chemical elements, the solar system, our earth, and all the living organisms

TABLE 1.1. A CHRONOLOGY OF THE EARLY UNIVERSE

Time since Big Bang	*Significant Events*
10^{-43} seconds	"Planck time"; the universe is smaller than the "Planck length," the smallest length that has any physical meaning; we can say nothing about what happened before this point, but gravity appears already as a distinct fundamental force.
10^{-35} seconds	"Strong" and "electromagnetic" forces begin to appear as distinct fundamental forces.
10^{-33}–10^{-32} seconds	"Inflation": the universe expands faster than the speed of light and cools to near absolute zero.
ca. 10^{-10}–10^{-6} seconds	As fundamental forces separate, the universe heats up again; quarks and antiquarks are created and annihilate each other; surviving quarks are confined in protons and neutrons (their total mass representing about one-billionth of the previous mass of quarks and antiquarks).
1–10 seconds	Electron–positron pairs form and annihilate (leaving a residue equivalent to perhaps one-billionth of the previous mass of electrons and positrons).
3 minutes	Nuclei of hydrogen and helium form from protons and neutrons.
300,000 years	Atoms form as negative electrons are captured by positive protons; the universe becomes electrically neutral, and radiation and matter separate; radiation is released in a huge "flash" now detectable in background microwave radiation.

SOURCES: Cesare Emiliani, *The Scientific Companion: Exploring the Physical World with Facts, Figures, and Formulas,* 2nd ed. (New York: John Wiley, 1995), p. 82; and see the similar chronology in Stephen Hawking, *The Universe in a Nutshell* (New York: Bantam, 2001), p. 78.

that inhabit our earth. Finally, of course, they include ourselves. As an anonymous wit is supposed to have put it: "Hydrogen is a light, odorless gas which, given enough time, changes into people."[25] From this perspective, the modern creation myth is as paradoxical as any other early creation myth. Nothing changes; but everything changes. Though things seem to exist independently of each other, and to have particular and distinctive characteristics, it is also true that everything is really the same. The idea that form and matter are different expressions of the same underlying essence was proposed by the Italian Giordano Bruno as early as 1584, in a book called *Concerning the Cause, Principle, and One.* But the same idea occurs in much deep religious and philosophical thought. According to one of the holiest of Buddhist texts, the Heart Sutra, "Form is emptiness; emptiness also is form. Emptiness is no other than form; form is no other than emptiness."[26] How patterns were created out of the apparent chaos of the early universe will be one of the central themes of the next chapter.

EVIDENCE FOR BIG BANG COSMOLOGY

From these metaphysical speculations, we must return to the prosaic but crucial issue of evidence. Why do modern astronomers accept what seems, at first sight, such a bizarre creation story? Why should we take this story seriously? The short answer is that for all its oddity, the modern story of creation is based on a colossal amount of hard evidence.

Hubble and the Redshift

The first crucial piece of evidence emerged from studies of the size and shape of the universe. Mapping the universe meant trying to determine the distance between the stars, the way in which stars were arranged, and how they moved relative to each other. Modern attempts to map the universe scientifically date to the late nineteenth century.

Finding the distance to stars is extremely difficult. With nearby stars, it is possible to estimate distances using elementary trigonometry and exact measurements of a star's parallax. The largest baseline available to Earth-bound astronomers is Earth's orbit around the Sun, so astronomers look for stars whose positions appear to shift when observed at six-month intervals. But even this approach requires measurements that were too precise for any astronomers before the nineteenth century (see figure 1.1).

For more distant stars, we have to rely on methods that are even less precise. In the first decade of the twentieth century, an American astronomer, Henrietta Leavitt, studied variable stars—that is, stars whose brightness varies in a regular cycle. She discovered that in a particular type of variable star, the so-called Cepheid variables, the cycle reflected the size and the brightness of the stars. What made the Cepheids seem to grow by turns brighter and then darker was their expansion and contraction. Leavitt showed that the larger (and therefore brighter) Cepheids expand and contract more slowly. So, by measuring the length of the cycle, astronomers could estimate the size and therefore the *real* (or "intrinsic") brightness of each Cepheid variable. Then, by measuring the brightness it *appeared* to have to an observer on the earth, they could estimate how much light had been lost in the journey to our earth, and therefore how far away the star really was.

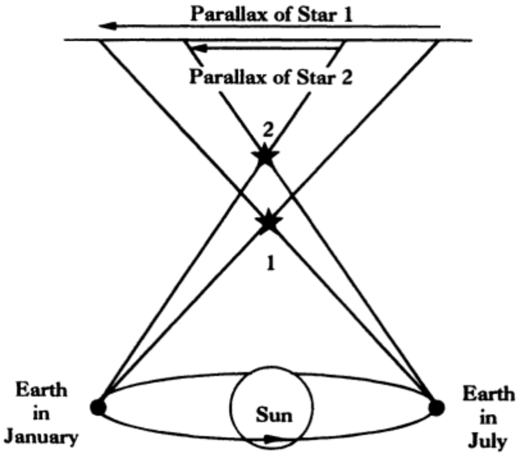


Figure 1.1. Parallax: measuring the distance of stars using elementary trigonometry. In the course of six months, the earth changes its position in the sky as it orbits the Sun. As a result, the positions of nearby stars seem to shift slightly during the year; and the closer stars are, the greater their apparent change in position. (A shift in the apparent position of an object caused by movements of the observer is known as *parallax*.) By measuring these shifts carefully, you can use elementary trigonometry to determine a star's real distance from the earth. This was the first way of determining the real scale of the cosmos. With more distant stars, the angles are too tiny for this method to work, so other methods have to be used. From Ken Croswell, *The Alchemy of the Heavens* (Oxford: Oxford University Press, 1996), p. 16. Used by permission of Doubleday, a division of Random House, Inc.

In the 1920s, another American astronomer, Edwin Hubble, using the Mount Wilson telescope outside Los Angeles, relied on Cepheid variables as he tried to map large areas of the universe. He found, first, that many Cepheids apparently existed outside our galaxy, the Milky Way. This meant that the universe consisted not just of one galaxy but of many, thereby proving an idea that the German philosopher Immanuel Kant had proposed almost two centuries before. (Specifically, Kant suggested quite correctly that the objects astronomers call *nebulae* often consisted of separate galaxies, well beyond our own.) This idea, which Hubble announced in 1924, already marked a revolution in modern astronomy. Within a few years, Hubble's work led him to an insight that was even more revolutionary, and much more profound. In the late 1920s, he found that most distant galaxies seemed to be moving away from us. Indeed, the farther away they were, the faster they seemed to be moving away from our galaxy. We now know that the most distant observable galaxies are moving away from us at more than 90 percent of the speed of light. How could Hubble know this? And what did this strange observation mean?

Oddly, it is easier to measure whether distant objects are moving toward or away from us than to determine their exact distance from us. The techniques involved are elegant, and not too difficult to grasp. If we take the light from a distant star and pass it through a spectrometer, we can analyze the various parts of the light spectrum. This is like watching sunlight through a prism. Different frequencies are bent by different angles as they pass through a prism; thus, as they leave the prism, they are displayed in bands of different colors like a rainbow. Each band, or color, represents light of a certain energy or frequency; and once they are split up in this way, each energy level can be studied separately. In star spectra, including that of our sun, narrow dark lines appear at particular frequencies. Studies in laboratories have shown that these lines occur because as light travels toward us, it passes through materials that absorb energy at particular frequencies, ensuring that those frequencies reach us in a weakened form. These darker lines are known as *absorption lines.* Each absorption line corresponds to a particular element, which absorbs light energy at specific frequencies. Remarkably, this means that by studying the absorption lines in starlight, we can estimate what elements are present in stars and in what quantities. Indeed, modern knowledge of how stars work (see chapter 2) is based largely on such studies.

Even more remarkably, star spectra can tell us whether a star is moving toward or away from us, and at what speed. The principle here is that of the Doppler effect—the phenomenon that makes an ambulance siren seem to drop in pitch as it passes by us. If a moving object (such as an ambulance) emits energy in waves (such as sound waves), those waves appear to be squashed up if the object is moving toward us, and stretched out if it is moving away from us. On a beach, if you walk into the surf, the wave crests will seem to strike your legs more frequently than if you stand still. But if you walk *toward* the beach, the crests will strike your legs less frequently. The same principle applies to light spectra. In the light from stars, absorption lines often seem to be shifted slightly from the position you would expect in a laboratory. Thus, the absorption line that represents hydrogen might be shifted to a higher frequency, making its light waves appear to be squashed up (or closer to the blue end of the spectrum). Or it might be shifted to a lower frequency (closer to the red end of the spectrum), in which case its light waves would appear to be stretched out. Hubble found both types of shift. But as he worked on the remotest objects, he realized that these were all shifted toward the red end of the spectrum. In other words, they appeared to be stretched out as if they were moving away from us. And the farther away they were, the greater the extent of the redshift.

The implications of Hubble's discovery are spectacular but simple to comprehend. The farther a galaxy is from the earth, the faster it is moving away from us, although stars in our own galaxy and some neighboring galaxies are held together by gravity. We have no reason to think that we live in an abnormal part of the universe. Indeed, modern maps of the distribution of galaxies suggest that the universe really is pretty homogenous on the largest scales. So we have to assume that other observers in any other part of the universe would also observe that other parts of the universe seemed to be moving away from them. And this must mean that the universe as a whole is expanding. If the universe is expanding, then in the past it must have been much smaller than it is now. If we follow this logic back in time, we will soon see that at some point in the distant past, the universe must have been infinitesimally small. This argument leads directly to the basic conclusion of modern big bang cosmology: the universe was once infinitesimally small, but it then expanded, and it continues expanding to the present day. Hubble's work provided the first and still the most basic evidence for big bang cosmology.

Hubble also showed that by measuring the rate of expansion, scientists should be able to estimate how long the universe has been expanding. This was an astonishing conclusion, for it seemed to imply something totally unexpected. Hubble had found a way of measuring the age of the universe! Originally, he calculated that the rate of expansion (or the *Hubble constant*) was ca. 500 kilometers per second for every megaparsec of distance between two objects. (A megaparsec is the distance traveled by light in 3.26 million years, which is ca. 30.9×10^{18} km, or ca. 30 billion billion km.) This figure meant that the universe could only be about two billion years old. We now know that this is an impossible date, as the earth itself is at least twice this age. Modern estimates of the Hubble constant are lower, and imply an older universe. But determining exactly how old remains tricky, mainly because of the difficulty of calculating the real distance to remote galaxies. Modern attempts, which use several other types of distance markers in addition to Cepheid variables, suggest that the Hubble constant lies between 55 and 75 km per second per megaparsec. These figures imply that the universe is between 10 and 16 billion years old, and the most recent estimates seem to be converging on a figure of about 13 billion (13,000,000,000) years.[27] For simplicity's sake, that is the date used throughout this book.

Relativity and Nuclear Physics

In the early twentieth century, most astronomers still assumed that the universe was infinite, homogenous, and stable. Hubble's conclusions would have seemed very odd if it had not been for some other developments that were undermining the traditional picture. One was the publication of Einstein's theory of relativity. The details of his theory are not important here, but one implication is that at the largest scales, the universe was probably unstable. Einstein's equations suggested that the universe, like a pin standing on its end, had to fall to one side or the other. It had to be either expanding or contracting; a perfectly balanced universe was very unlikely. Einstein himself resisted this conclusion. Indeed, in what he later described as the greatest error of his life, he altered his theory by proposing the existence of a force he called the "cosmological constant," in order to preserve the idea of a stable universe. This force he imagined as a sort of antigravity, which could counterbalance gravity and thus prevent the universe from collapsing in on itself. However, in 1922 a Russian, Alexander Friedmann, showed that the universe really might be either expanding or contracting. Eventually, even Einstein accepted the idea of an unstable and evolving universe.

But it took time to work out the ramifications of these discoveries. In the 1940s, the idea of an expanding universe still seemed odd to most astronomers. Then, between the 1940s and the 1960s, new evidence accumulated in support of the idea until, by the late 1960s, the big bang theory had become the standard account of the origins of the universe. In the late 1940s, using some of the knowledge gained from work on the atomic bomb, a number of physicists in the United States—including the Russian American physicist George Gamow—began to work their way through the implications of this new view of the universe. What would a tiny universe look like? It was clear that it would have been extremely hot: just as a bicycle tire becomes hotter when more air is pumped in, so the universe must have been extremely hot when all its matter and energy was squashed into a tiny space. The details of how matter would behave under such conditions do not concern us here. What matters is that scientists such as Gamow and later Fred Hoyle (who was to become a fierce critic of big bang cosmology) soon realized that it was possible, using existing ideas about how energy and matter worked at different temperatures, to start doing some calculations about the behavior of the early universe. And the answers made sense. They found they could construct a surprisingly plausible picture of how the early universe was constructed under the assumptions of the big bang theory. In particular, it was possible, roughly, to work out what forms of energy and matter would have existed in the early universe, and determine how that universe would have changed as it expanded and cooled. It soon became apparent that the idea of an early, dense, and hot universe was perfectly consistent with all that was known in the emerging field of particle physics.

Cosmic Background Radiation

What finally persuaded most astronomers to accept the big bang theory was the discovery of cosmic background radiation, or CBR. Early theories of how a big bang might have worked suggested that as temperatures fell during the early history of the universe, distinct particles and forces would acquire a stable existence as soon as temperatures were low enough for them to survive. As we have seen, for several hundred thousand years the early universe was too energetic and too hot for atoms to form. But eventually temperatures fell low enough for protons (with their positive electrical charges) to capture electrons (which have a negative charge). At this point, matter became electrically neutral, and energy and light could flow freely through the universe. Some of the earliest theorists of big bang cosmology predicted that there ought at that moment to have been a huge release of energy, whose remnants might be detectable today.

It is a sign of the caution with which scientists still approached the idea of a big bang that no one actually looked for this background energy. It was found accidentally, in 1964, by Arno Penzias and Robert Wilson, two scientists working for Bell Laboratories in New Jersey. They were trying to build extremely sensitive radio antennae, but found it was impossible to eliminate all the background "noise" they picked up. Eventually, they realized that wherever they pointed their antennae, there was always a faint hum of weak energy. What could possibly be emitting energy from all directions of the sky at the same time? Energy coming from a particular star or galaxy made sense, but energy coming from *everywhere*—and *so much* energy—seemed to make no sense at all. Though the signal was weak, the total when all the energy it represented was added up was colossal. They mentioned their discovery to a radio astronomer who had heard a talk by a cosmologist, P. J. E. Peebles, predicting the existence of remnant radiation at an energy level equivalent to a temperature of ca. 3°C above absolute zero.

This was remarkably close to the temperature of the radiation found by Penzias and Wilson. They had found the flash of energy predicted by early theorists of the big bang.

Their discovery was decisive because no other theory could explain such a universal and powerful source of energy, while big bang cosmology could explain it naturally and easily. Since 1965, few astronomers have doubted that the big bang theory is the best current explanation for the origins of the universe. It is now the central idea of modern astronomy, the paradigm that unifies the theories and ideas of modern astronomy. And the cosmic background radiation is central to modern cosmology: attempts to map tiny variations in it should provide us in the near future with the best information available on the nature of the early universe. (One cosmologist, Dr. Max Tegmark, has even suggested that "the Cosmic microwave background is to cosmology what DNA is to biology.")[28] A new satellite, the Wilkinson Microwave Anisotropy Probe, or WMAP, which was launched in June 2001, is designed to describe these tiny variations more precisely than ever before.[29]

Other Forms of Evidence

More evidence for the big bang has accumulated since the discovery of the CBR. For example, the big bang theory predicts that the early universe will consist mainly of simple elements, above all hydrogen (ca. 76 percent) and smaller amounts of helium (ca. 24 percent). These are about the ratios we observe in the universe today (though the amount of hydrogen has fallen to ca. 71 percent as reactions within stars have converted hydrogen into helium, which now accounts for ca. 28 percent of all matter). The chemical dominance of hydrogen and helium is not immediately obvious to us, because we live in a corner of the universe that happens to have high concentrations of other elements (see chapters 2 and 3), but the evidence is all around us nonetheless. Hydrogen is by far the most common element, even in our own bodies. As Lynn Margulis and Dorion Sagan write: "Our bodies of hydrogen mirror a universe of hydrogen."[30] Especially precise measurements have also been made of the tiny amounts of lithium created in the big bang. These, too, are remarkably close to the figure predicted by theories of element formation during the big bang.

Then there is the fact that neither astronomical observations nor radiometric dating techniques (see appendix 1) can identify any objects that are much more than 12 billion years old. If the universe had in fact existed for much longer than this (perhaps for several hundred billion years), the absence of any objects older than a cutoff date of 12 billion years would be extremely surprising.

Finally, the big bang theory—unlike its main rival, the steady state theory—implies that the universe has changed over time. This means that the most distant parts of the universe ought to seem different from those closer to us; for in looking at objects, say, 10 billion light-years away, we are in effect looking at the universe as it was 10 billion years ago. And, as we will see, distant objects *are* different from the modern universe in important ways. For example, the early universe contained many more quasars (see chapter 2) than does the modern universe.

How Trustworthy Is Big Bang Cosmology?

Is big bang cosmology true? No scientific theory can claim absolutely certainty. And there remain problems with the theory, some of which are highly technical. But at present, none of these problems seems insurmountable.

For a time in the early 1990s, it appeared that some stars were older than the apparent age of the universe—evidence, according to some astronomers, that cast serious doubt on the entire theory. Observations using the Hubble telescope have since shown that this is not true. The oldest stars now seem to be about one billion years younger than the date of the universe as determined by the latest estimates of the Hubble constant. This is good news for big bang cosmology! But there was less welcome news when, in the late 1990s, evidence began to accumulate from studies of distant Ia type supernovae (see chapter 2) that the rate of expansion of the universe, rather than decreasing under the influence of gravity, is in fact increasing. If these observations are correct, they are startling, for they seem to imply that there exists some hitherto unknown force that has operated constantly since the big bang to maintain and accelerate the rate of expansion, but that is too weak to have been detected before. One possibility is that this force consists of "vacuum energy," a force predicted by quantum mechanics that would act in a way opposite to gravity, driving matter and energy apart rather than drawing them together. If so, its effects may be almost identical to those of Einstein's speculative cosmological constant.[31] This evidence may throw a largish wrench into the machinery of big bang cosmology. On the other hand, it may provide an unexpected solution to the problem of dark matter (see chapter 2), because vacuum energy, like all energy, has mass, which may account for a substantial amount of the matter that astronomers have been looking for. There is also the tricky problem of beginnings. At the beginning of the big bang, all our scientific knowledge seems to go haywire. The density of the universe seems to move toward infinity, as does its temperature, and modern science has no good way of dealing with such phenomena, though it has many promising ideas.

What encourages us to take the theory seriously despite these difficulties is its consistency with most of the empirical and theoretical knowledge assembled by modern astronomy and modern particle physics. And no other theory of origins can explain so much. That scientists have constructed a logical theory consistent with so much evidence, and one that seems to tell us what happened during the first few minutes of our universe's history, is itself an astonishing achievement. It is no less remarkable when we realize that future research is likely to modify the current theory, perhaps in quite significant ways.

NOTE ON EXPONENTIAL NOTATION

Modern science often deals with large quantities and large numbers. Writing out, say, a billion billion billion would take a lot of space (to see how much, look at the second paragraph of this note), so scientists use what they call *exponential notation;* a number of figures in this chapter use this convenient mathematical shorthand. Here is how it works.[32] One hundred is 10 multiplied by 10, or two 10s multiplied together. In exponential notation, 100 can be written as 10^2. One thousand is three 10s multiplied together, or 10^3, and so on. To convert a number in exponential notation to one in normal notation, write down a 1, then add the number of zeros that appear in the exponent. One thousand (10^3), therefore, is 1 with three zeros after it; one billion is 10^9, or 1 with 9 zeros after it—that is, 1,000,000,000. We can use the same notation for small numbers, too. One hundredth ($\frac{1}{100}$ or 1 percent) is written as 10^{-2}; and one thousandth ($\frac{1}{1000}$) is written as 10^{-3}. The system also works well for numbers that are not an exact multiple of ten. Thus 13 billion years can be thought of as 13 times a billion years. In exponential notation this becomes 13×10^9 years.

The crucial thing to note is that increasing the exponent by one *multiplies* the size of the previous number ten times. So 10^3 is not just slightly bigger than 10^2; it is, in fact *ten times as large.* In the same way, 10^{18} (or a billion billion) is not double the size of 10^9; it is one billion times (10^9 times) as large; and it is ten times as large as 10^{17}. Exponential notation provides a deceptively simple way of describing colossal numbers, which can easily lull us into forgetting how large these numbers really are. The mass of a hydrogen atom can be written in exponential notation as 1.7×10^{-27} kilograms. In ordinary script, this is a simple, but lengthy, fraction: 1.7/1,000,000,000,000,000,000,000,000,000 kilograms, or 1.7 times one billionth of a billionth of a billionth of a kilogram. To understand what this really means is trickier. Try to imagine something so small that it weighs just one-billionth of a kilogram. (We cannot do it, of course—our minds are not designed to deal with such calculations; but we can make the effort.) Then try to imagine something that weighs one billionth of this; then repeat the experiment a third time, and you are imagining the size of a hydrogen atom. To weigh the Sun, you multiply instead of dividing. The Sun has a mass of about 2×10^{27} tons, or 2,000,000,000,000,000,000,000,000,000 tons, which is two times a billion billion billion tons. It contains about 1.2×10^{57} atoms. The universe contains about 10^{22} stars. To roughly estimate the number of atoms in the universe, we can multiply these two numbers together, which means *adding* the two exponents, to get 1.2×10^{79} atoms. This may not seem so impressive until we start writing the number out in ordinary notation, and even then, most of us cannot really understand what we are writing down. In the final chapter of this book, we will come across numbers much, much larger than even these huge figures.

SUMMARY

Before about 13 billion years ago, we can say nothing with any confidence about the universe. We do not even know if space and time existed. At some point, energy and matter exploded out of the emptiness, creating both time and space. The early universe was fantastically hot and extremely dense, and it expanded extraordinarily fast in a sort of cosmic explosion. As it expanded, it cooled. Matter and antimatter annihilated each other, leaving a tiny residue of matter. Out of the violent flux of the early universe, there appeared distinct entities—protons, neutrons, photons of light, electrons—and distinct forces, including the strong force, the weak force, and the forces of gravity and electromagnetism. After a few hundred thousand years, the universe was cool enough for protons and electrons to form stable atoms, and the matter in the universe became electrically neutral. As a result, matter and energy ceased to interact constantly, and radiation began to flow freely through the universe. As the universe expanded, the temperature of the radiation fell; it is now detectable as the cosmic background radiation.

This story, as strange as it may seem, is based on a colossal amount of scientific research, and it is compatible with most of what we know today about astronomy and particle physics. Big bang cosmology is now the central idea of modern cosmology. It is the paradigm that unites modern ideas on the nature and history of the universe, and it dominates the first chapter of the modern creation myth.

FURTHER READING

Barbara Sproul's *Primal Myths* (1991) is a collection of creation myths from many different cultures, accompanied by an introductory essay. There are now many popular accounts of big bang cosmology, some by authors who helped construct the modern story of the origins of the universe. The following are some of the books I have found most helpful. Stephen Hawking's *A Brief History of Time* (1988) is one of the best known, and has recently been followed by his *The Universe in a Nutshell* (2001); even more technical is Steven Weinberg, *The First Three Minutes* (2nd ed., 1993). John Gribbin's *Genesis* (1981) is a superb introduction for the general reader (and one of the inspirations for this book), though it's beginning to show its age. More up-to-date, though equally readable, are Timothy Ferris, *The Whole Shebang* (1997); John Barrow, *The Origin of the Universe* (1994); Peter Coles, *Cosmology* (2001); and Armand Delsemme, *Our Cosmic Origins* (1998). Delsemme's book is relevant for much of the first half of this book. Cesare Emiliani's *Scientific Companion* (1995) is a useful handbook for those who want more precise information about the ideas and terminology of modern astronomy, chemistry, and physics. Eric Chaisson's *Cosmic Evolution* (2001) is an attempt to think through the meaning of order and entropy at many different scales, from stars to microbes, and Martin Rees's *Just Six Numbers* (2000) is also about the fundamental structures of the universe. Lee Smolin's *Life of the Cosmos* (1998) is a readable book that consists of grand speculations about the possibility that our universe is one of a vast population of universes that change according to some form of cosmic evolution. Charles Lineweaver's short essay "Our Place in the Universe" (2002) is a marvelous introduction to the challenge of thinking about scale and orientation within the universe. Nigel Calder's *Timescale* (1983) is a remarkable chronology for the whole of time, though it is now old enough to be slightly dated.

2

ORIGINS OF THE GALAXIES AND STARS

THE BEGINNINGS OF COMPLEXITY

If one had to summarize, in just one sentence, "What's been happening since the Big Bang?," the best answer might be to take a deep breath and say: "Ever since the beginning, gravity has been moulding cosmic structures and enhancing temperature contrasts, a prerequisite for the emergence of the complexity that lies around us ten billion years later, and of which we are part."

Look at the sky on a clear night, and it seems obvious that stars are the most important inhabitants of our universe. But stars, like humans, do not exist in isolation. They gather into the huge cosmic societies we call *galaxies,* each of which may contain 100 billion stars. Our home galaxy is the Milky Way. Unlike other galaxies, which appear to us as faint stars or blurs, the Milky Way looks like a pale river of light flowing across the night sky, because we see it from inside. What is less obvious to the naked eye, and was not apparent even to most astronomers until a decade or two ago, is that galaxies gather into even larger communities. These include *groups* (usually a few million light-years in diameter, containing perhaps twenty galaxies) and *clusters* (up to 20 million light-years broad and holding hundreds, even thousands, of galaxies). Groups and clusters of galaxies are held together by gravitational forces. But there exist even larger structures, structures so large that they are stretched out by the expansion of the universe. These include *superclusters* (up to 100 million light-years across, with perhaps 10,000 galaxies) and the huge chains of superclusters enclosing vast bubbles of empty space that were first detected by astronomers in the 1980s. At even larger scales, the universe appears to be remarkably homogenous. This homogeneity shows up in the uniformity of the cosmic background radiation. So the complex pat-

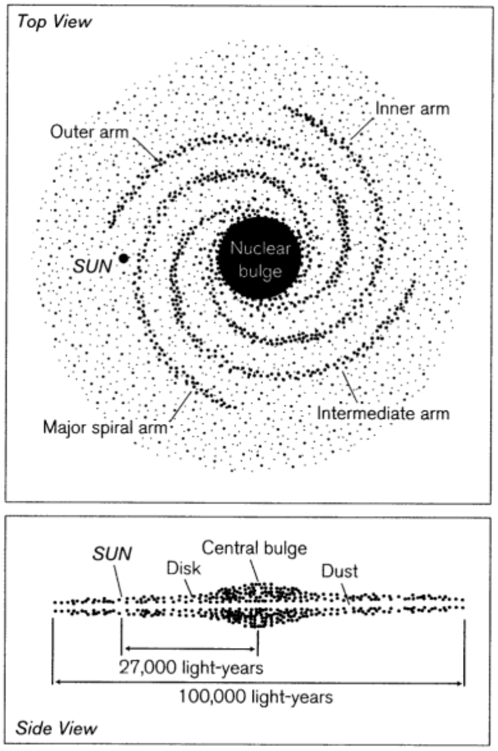


Figure 2.1. The position of the Sun within the Milky Way. The Sun lies within an arm of the Milky Way, about 27,000 light-years from its center. Clouds of dust obscure our view of the central parts of the galaxy. Adapted from Nikos Prantzos, *Our Cosmic Future: Humanity's Fate in the Universe* (Cambridge: Cambridge University Press, 2000), p. 97.

terns that will interest complex observers such as ourselves seem to appear only at scales smaller than chains of superclusters.

At present, these seem to be the largest ordered structures in the observable universe. Their discovery pushes us even farther from the center of the universe than Copernicus's discovery that the earth revolved around the Sun. Our sun, it seems, is situated in an undistinguished suburb in a second-rank galaxy (the Andromeda Galaxy is the largest in our local group), in a group of galaxies that lies toward the edge of the Virgo Supercluster, which contains many thousands of other galaxies (see figure 2.1).[1]

More recently, it has become clear that even superclusters may be mere bit players in the history of the universe. It seems that most of the mass of the universe (90 percent or more) is *not* visible, and the exact nature of this mass (known appropriately as *dark matter*) remains a mystery. In other words, we are in the embarrassing position of not knowing what most of the universe is made of.[2] This chapter will touch on theories about the nature of dark matter, but it will focus mainly on those parts of the universe that we know most about—those parts that are visible.

We take up the history of the early universe where we left it in the previous chapter: about 300,000 years after its creation, as energy and matter went their separate ways.

THE EARLY UNIVERSE AND THE FIRST GALAXIES

In the first minutes of its existence, the universe cooled so rapidly that it was impossible to manufacture elements heavier or more complex than hydrogen, helium, and (in minute amounts) lithium: elements 1, 2, and 3 in the periodic table. In the heat and chaos of the early universe, nothing more complex could survive. From a chemical point of view, the early universe was very simple, far too simple to create complex objects such as our earth or the living organisms that inhabit it. The first stars and galaxies were constructed from little more than hydrogen and helium. But they were a sign of our universe's astonishing capacity to build complex objects from simple building blocks. Once created, stars laid the foundations for even more complex entities, including living organisms, because in their fiery cores they practiced an alchemy that turned hydrogen and helium into all the other elements of the periodic table.

So far, the story of the universe has been dominated by the expansionary force of the big bang. Now we must introduce a second large-scale force: that of gravity. Gravity is the force that Newton described so successfully in the seventeenth century and that Einstein described even more precisely early in the twentieth century. While the force of the big bang drives energy and matter apart, gravity pulls things together. Newton argued that all forms of matter exert a tug on all other forms of matter. Einstein maintained that the effects of gravity arise because of the way that large masses can warp the geometry of space-time. Einstein also showed that gravity acts on energy as well as on matter. This conclusion was not entirely surprising, for Einstein had already demonstrated that matter is really a sort of congealed energy. But he went further, offering an ingenious proof that gravity can warp energy as well as matter. The Sun is the largest object in our solar system and has the greatest mass. He argued that its huge mass ought to bend the space-time around it enough to alter the trajectory of light rays passing close to the Sun's edge. The best opportunity for detecting this effect was during a solar eclipse, the only time when it was possible to see stars close to the Sun. If stars at the edge of the Sun were photographed just before a solar eclipse, he predicted that their movement would appear to slow down just before they passed behind the Sun. As they appeared on the other side, they would also seem to hover momentarily at the Sun's edge before moving away from it. This effect would result from beams of starlight being bent by the Sun's mass, just as a stick seems to bend when placed in water. In 1919, Einstein's prediction was tested during a solar eclipse and found to be astonishingly accurate.

By pulling on both matter and energy, gravity can give the universe shape and structure. It may be easiest to see how it does so if we stick with Newton's intuitively simpler notion of gravity as a "force." Newton showed that gravity can work at very large scales but is most powerful close-up. To be precise, the gravitational attraction between two objects is proportional to the (square of the) mass of the two objects, and is inversely proportional to the (square of the) distance between them. This means that gravity can pack closely packed masses even more closely together, but has less effect on objects separated by large distances. Gravity has even less impact on light, fast-moving objects such as the particles that carry energy, and thus it shapes matter more effectively than energy. Because its effects vary in these ways, gravity has managed to create many complex structures at a number of different scales. This is a remarkable conclusion, for it suggests that in some sense, and at some scales, gravity can temporarily counter the second law of thermodynamics, the fundamental law that seems to guarantee that over time, the universe will become less ordered and less complex (see appendix 2). Instead, as gravitational energy is released (as gravity clumps matter together), the universe appears to become *more* ordered. Gravity is thus one of the major sources of order and pattern in our universe. In the rest of this chapter we will see how gravity created many of the complex objects studied by astronomers.

Much of the history of the early universe, and of the galaxies and stars, can be thought of as a product of competition between the force of the big bang, which drives the universe apart, and the force of gravity, which tends to draw the universe back together again. There is an unstable and shifting balance between these two forces, with expansion winning at the largest scales and gravity winning on smaller scales (up to the level of clusters of galaxies). But gravity needs some initial differences to work with. If the early universe had been perfectly smooth—if, say, hydrogen and helium had been distributed with absolute uniformity throughout the universe—gravity could have done little more than to slow down the rate at which the universe expanded. The universe would have remained homogenous; and complex, lumpy objects such as stars, planets, and . . . human beings could never have formed.

So it is important to know how homogenous the early universe was. Astronomers try to measure the "smoothness" of the early universe by looking for tiny differences in the temperature of the cosmic background radiation. Any "bumpiness" ought to show up as slight temperature differences in the cosmic background radiation. The COBE (Cosmic Background Explorer) satellite, launched early in the 1990s, was designed to look for such differences, and the WMAP (Wilkinson Microwave Anisotropy Probe) satellite, launched in June 2001, is mapping these variations with even greater precision. COBE has shown that although the cosmic background radiation is extremely uniform, there *are* tiny variations in its temperature. Apparently, some areas of the early universe were slightly hotter and denser than others. These "wrinkles" gave gravity some differences to work with, and it did so by magnifying them, making dense regions even denser. Within a billion years after the big bang, gravity had created huge clouds of hydrogen and helium. These may have been as large as several clusters of galaxies, and locally, their gravitational pull would have been sufficient to counteract the expansionary drive of the universe. At larger scales, the expansionary force of the big bang remained dominant, so that over time the gaps between these massive clouds of matter increased.

Under the pull of their own gravity, the clouds of hydrogen and helium began to collapse in on themselves, as atoms of hydrogen and helium were packed ever more closely together. As the gas clouds shrank, some regions became denser than others and began to collapse more rapidly; in this way, the original clouds broke into smaller and smaller clumps at many different scales, from that of whole galaxies to single stars. As gravity packed each cloud into ever smaller spaces, pressure built up in the center. Increasing pressure means increasing temperatures, and so, as they shrank, each gas cloud began to heat up. Within the smaller clumps, which contained a mass equivalent to several thousand stars, there appeared regions of enormously high density and extreme heat; it was in pockets within these cosmic nurseries that the first stars were born.[3]

As the core regions heated up, the atoms within them moved faster and faster, and collided more and more violently. Eventually, the collisions were violent enough to overcome the electric repulsion between the positively charged nuclei of hydrogen atoms. (These repulsive forces depend partly on the number of protons, or positive charges, in the nuclei, so this reaction occurs most easily in hydrogen atoms and becomes progressively more difficult to achieve with larger atoms.) Wherever temperatures reached 10 million degrees C, pairs of hydrogen atoms fused to form helium atoms, each of which has two protons in its nucleus. This nuclear reaction, known as *fusion,* is what happens at the center of a hydrogen bomb. As hydrogen atoms fuse into helium, a tiny amount of matter is transformed into a huge amount of energy according to Einstein's formula, $E = mc^2$: the energy released is equal to the mass that is transformed multiplied by the speed of light *squared.* Because the speed of light is an enormous figure, Einstein's equation tells us that an enormous amount of energy is released by the transformation of even tiny amounts of matter. To be precise, when hydrogen atoms fuse to form an atom of helium, they lose about 0.7 percent of their mass; we know this because a helium atom weighs less than the hydrogen atoms used to construct it. The lost mass has been converted into energy.[4] Stars are like massive hydrogen bombs with so much fuel that their "explosions" can continue for millions or even billions of years. And this is how the first stars lit up the billion-year-long night of the early universe.

The colossal heat and energy generated by fusion reactions resist the force of gravity, so as they light up, young stars stop collapsing. And it is this balance between the expansionary force of the nuclear explosions at their center and the attractive force of gravity that tames the violent energies at the heart of all stars. Stars form durable structures because they are the result of a negotiated compromise between gravity, which crushes matter together, and the explosive force of fusion reactions, which forces matter apart. The negotiations are continuous; if the center heats up, the star expands and thus cools down—so it contracts again, in a negative feedback cycle analogous to that in an air-conditioning system. (If the air gets too hot, the system switches on and cools the air down again.) We can watch these negotiations in the pulsations of variable stars. But normally, the underlying truce endures for millions or billions of years, as long as the star exists.

The lighting up of the first stars was a momentous turning point in the history of the universe, for it marked the appearance of a new level of complexity, of new entities operating according to new rules. What had been billions and billions of atoms, drawn together by the force of gravity, suddenly became a new organized structure—one that could last for millions or billions of years. The moment of transition occurred when a slight increase in temperature ignited fusion reactions throughout the core of the proto-star, thereby transforming gravitational energy into heat energy and creating a new and more stable system of energy flows. Stars organize the atoms they contain into new, durable configurations, which can handle huge energy flows without disintegrating. This, we will see, is the characteristic pattern of all such thresholds. New configurations emerge quite suddenly as once independent entities are drawn into new and more ordered patterns, held together by an increasing throughput of free energy (see chapter 4). But, as is true of all these structures, they are held together only with difficulty, so none is eternal. New levels of complexity are characterized, therefore, by a certain fragility and by the certainty of eventual collapse. The second law of thermodynamics ensures that all complex entities will eventually die; but the simpler the structure, the better its survival chances, which is why stars live so much longer than humans (see appendix 2).

Many of the first stars are still around today, 13 billion years later. Most can be found in the centers of galaxies, or in the huge balls of stars known as *globular clusters,* which orbit most galaxies in large spherical tracks. The earliest stars probably formed during the chaotic and rapid collapse of relatively formless clouds of gas. They can be detected today by their erratic orbits and by the absence of elements heavier than hydrogen and helium, because those were the only elements available when they were formed. In the crowded early universe, embryonic galaxies often blended into each other, and these mergers help explain the erratic orbits of many of the oldest stars.

As galaxies formed and merged in the early universe, gravity went to work on them, sculpting many into a shape that is surprisingly common in the universe. As the ragged galaxies of the early universe were pulled together by gravity, different parts were dragged toward the center in huge arcs; and minor variations in the movements of these arcs ensured that each cloud began to spin, like water going down a drain. As each cloud contracted, the rotation accelerated, as happens when skaters fold in their arms. Like a spinning ball of dough, the areas spinning fastest were flung out by centrifugal force, and the entire cloud began to flatten into a sort of cosmic pizza. These simple processes, all dominated by the force of gravity, explain why so many of the largest clouds of matter in the universe, even at the scale of galaxy clusters, take the form of spinning disks, which the Soviet theorist Yakov Zel'dovich has called "crepes." We will see that the same rules also operate at smaller scales, which is why our solar system would also look like a huge, flat disk if we could see it from a distance.

By the time a second generation of stars began to form, these processes had transformed some of the larger galaxies, such as the Milky Way, into huge and more or less regular disks. This change is reflected in the more orderly orbits of younger stars, such as our own sun, which, traveling at the stately speed of 800,000 kilometers an hour, takes about 225 million years to process once around the center of the Milky Way. Similar mechanisms shaped other galaxies, creating a universe populated by galaxies of stars, constructed in different ways but often forming regular, rotating disks. Star formation continues to the present day. In the Milky Way, about ten new stars are formed every year.

A COSMOLOGICAL MENAGERIE: BLACK HOLES, QUASARS, AND DARK MATTER

The early universe contained stranger objects than stars. At the center of most galaxies, densities were so great that huge clouds of matter and energy kept collapsing even at temperatures high enough to start fusion reactions. Here, gravity acquired such momentum that it crushed matter and energy out of existence, thereby forming the bodies called *black holes.* Black holes are regions of space so dense that no matter and no energy can escape their gravitational pull, not even light. This means we can never directly observe what goes on inside a black hole, except by entering it—and then, of course, we could never return to report our findings. Black holes are so dense that to form one from our earth, we would have to crush it into a ball with a diameter of about 0.7 inches.[5]

There has been much fascinating speculation about the true significance of black holes. Recently, for example, it has been suggested that black holes may be what new universes look like from the outside. Each may represent a separate universe, beginning with its own big bang. Lee Smolin has argued that if this is true, we may have an explanation for some other oddities of our universe. In particular, we may be able to explain why so many crucial parameters—such as the relative strength of the fundamental physical forces, or the relative size of fundamental nuclear particles—seem precisely tuned to create a universe capable of producing stars, elements, and complex entities such as ourselves. On Smolin's assumptions, only universes that can produce black holes can have "offspring." If we add a further assumption, that new universes differ only slightly from their "parent" universe, we see that a process akin to Darwinian selection may be at work.[6] After many generations, the hyperspace in which these many universes exist is likely to be dominated by those universes that have the precise qualities needed to produce black holes, however statistically improbable these universes may be, because all other universes will be sterile. But if a universe can produce black holes, it can probably produce other large objects as well, such as stars, and many other kinds of complex structures besides. Such ideas suggest that there may be new levels to our modern creation myth above the level of the universe, and that a "hyperuniverse" could exist that is far older than 13 billion years, and much bigger than our universe. But at present, we have no way of proving or disproving these grandiose ideas.

So we can safely return from these speculations to the universe we know. Black holes can tell us some important things about our own universe and the galaxies that populate it. They are so dense that the gravitational forces they exert can generate energies much larger than those produced within stars. It is likely that a black hole lurks at the center of the Milky Way, 27,000 light-years away in the direction of the constellation Sagittarius. It may be identified with a powerful source of radio waves known as Sagittarius A, and it probably has a mass about 2.5 million times that of our own sun.

The existence of black holes at the center of many galaxies may help explain another strange object, the quasar, or "quasistellar radio source." The first quasars, the brightest objects known to modern astronomy, were detected by Australian astronomers in 1962. They shine more brightly than even the largest galaxies, though they are no larger than our solar system. They are also extremely remote. Most are more than 10 billion light-years away, and none is closer than 2 billion light-years from us. So when we look at quasars, we are seeing objects that existed early in the universe's life. Currently, it seems likely that their energy comes from huge black holes that suck in large amounts of matter from the galactic material surrounding them. Quasars thus consist of black holes plus star food. Quasars were particularly numerous early in the life of the universe, because at that time galaxies were crowded more closely together, and black holes were better fed. Since then, the universe has expanded, galaxy clusters have moved farther apart, and the pickings have become leaner for galactic black holes. So, though most galaxies may still have black holes at their centers, few of these beasts now consume enough to create quasars. And as most quasars do not live more than a few million years because of their prodigious appetite for star dust, they are rare in the modern universe. Quasars are the astronomical equivalent of dinosaurs, though the black holes that powered them still survive at the centers of most galaxies, waiting for unwary stars to fall into their clutches.

Galaxies and stars make up most of the visible universe. But observations of the movements of galaxies and galaxy clusters have led to the embarrassing conclusion that we are seeing only a tiny part of what is actually out there. Indeed, what we can *see* may constitute no more than 10 percent, and perhaps as little as 1 percent, of the matter in the universe. Using the basic laws of gravity, astronomers can calculate roughly how much matter is in a group of galaxies by studying the way they rotate, and such studies