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The Universe Before the Big Bang

Cosmology and String Theory

Springer

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To Patrizia and Daniela

Preface

The idea of preparing this book grew out of a series of lectures and seminars held over several years in various Italian universities. The interest aroused in the students – and in colleagues not specialized in the field, who were also present at the talks – led me to the idea of writing a non-technical introduction to the newly-born field of string cosmology, aimed at a wider range of readers than just the professional community who usually attend the international conferences and read the specialized journals.

The challenge with this book is to present new possible scenarios for the primordial Universe emerging from recent developments in theoretical physics, but without resorting to too many numbers and equations, and using instead a series of illustrative cartoons. The book is addressed, in particular, to all those readers with at least a basic (high-school) knowledge of physics, but not necessarily equipped with an academic scientific background.

As a consequence, the discussion of many issues will be qualitative, often incomplete, and sometimes even grossly approximate. Nevertheless, I hope that the introductory picture provided by this book will be detailed enough to enable the reader to understand the most recent cosmological models, the key underlying ideas and, above all, how they can be tested using the experimental tools provided by current technology.

The physical grounds for such ideas are deeply rooted in the so-called theory of strings (or *string theory*, for short). Within modern physics, string theory provides in principle a robust theoretical framework for a complete and unified description of all the forces of Nature, at all energies – actually, it is at present the *only* theoretical scheme able to include the gravitational force in a consistent way, even in the quantum regime. One of the possible consequences of string theory is a cosmological scenario in which the great initial deflagration commonly called the *Big Bang* may not necessary coincide with the birth of our Universe; rather, it could represent just an intermediate step in the whole history of the cosmos. Given the potential relevance of this picture (and the possible impact even beyond its strictly scientific applications), it is probably appropriate to attempt to put it across to a non-specialist audience.

The present version of the book is partly based on an earlier Italian edition, which has been extensively brought up to date taking into account the most recent – theoretical and experimental – developments in the physics of the early Universe. I should mention, in particular, the latest (2006) results of the WMAP satellite on the experimental side, and the inflationary scenarios based on brane interactions on the theoretical side. In addition, the former edition has been completed by new figures and new important explanatory parts concerning string theory and its revolutionary impact on our understanding of fundamental physics.

It is a pleasure, as well as a duty, to thank the many researchers with whom I have worked over the years on various aspects of string cosmology, and whose collaboration I hope to continue. They are, in alphabetical order: Luca Amendola (Observatory of Rome, Italy), Valerio Bozza (University of Salerno, Italy), Ram Brustein (Beer Sheva University, Israel), Alessandra Buonanno (University of Maryland, USA), Cyril Cartier (University of Geneva, Svitzerland), Marco Cavaglià (University of Mississippi, USA), Eugenio Coccia (University of Rome "Tor Vergata", Italy, currently Director of the Gran Sasso National Laboratory, L'Aquila, Italy), Edmund Copeland (University of Nottingham, UK), Giuseppe De Risi (University of Bari, currently at the University of Portsmouth, UK), Ruth Durrer (University of Geneva, Switzerland), Massimo Giovannini (University of Turin, Italy, currently at CERN, Switzerland), Michele Maggiore (University of Geneva, Switzerland), Jnan Maharana (Bubaneshwar University, India), Kris Meissner (University of Warsaw, Poland), Slava Mukhanov (University of Munich, Germany), Stefano Nicotri (University of Bari, Italy), Federico Piazza (University of Milan "Bicocca", Italy, currently at the Perimeter Institute for Theoretical Physics, Canada), Roberto Ricci (University of Rome "Tor Vergata", Italy), Mairi Sakellariadou (University of Athens, Greece, currently at King's College, London, UK), Norma Sanchez (Observatory of Paris, France), Domenico Tocchini-Valentini (Observatory of Rome, Italy, current at The Johns Hopkins University, Baltimore, USA), Carlo Ungarelli (University of Pisa, Italy), and Gabriele Veneziano (Collège de France, Paris). Beside these people there are many other scientists who have originally and independently contributed to the cosmological models presented in this book, and to whom I will make reference in the subsequent chapters (see also the website dedicated to string cosmology available at the address http://www.ba.infn.it/~gasperin).

I would also like to thank the various national and international scientific collaborations that have kindly permitted the use of figures and photos regarding gravitational wave and cosmic microwave experiments. I am grateful, in particular, to the following scientists (in alphabetical order): Peter Bender (University of Colorado, USA, on behalf of the LISA collaboration), Massimo Cerdonio (University of Padua, Italy, on behalf of the AURIGA collaboration), Adalberto Giazotto (INFN Pisa, Italy, on behalf of the VIRGO collaboration), and Jan Tauber (ESA Astrophysics Division, on behalf of the PLANCK collaboration).

However, there are not enough words for thanking my collaborator and friend Gabriele Veneziano, former staff member (and former Director of the Theory Division) of the European Center for Nuclear Research (CERN) in Geneva, Switzerland, now Professor at the Collège de France, in Paris. Gabriele started the original project for this book with me, but unfortunately was unable to pursue it due to later commitments. Despite that, he has generously helped me to write the chapter specifically devoted to strings – and indeed, he is a world-renowned expert on strings, besides being one of the founding fathers of string theory – and his advice has also been invaluable in many other parts of the book. It is fair to say that this book would not exist in its present form without his original contributions and the passionate commitment to research that we have shared over many years. So any credit for the book is also partly his due, while I assume full responsibility for any imperfections.

Last but not least, I am very grateful to Angela Lahee (Physics Editor at Springer) for her kind encouragement and advice, and for many important suggestions. I am also grateful to Carlo Ungarelli for his careful translation of the original Italian manuscript. Finally, special thanks are due to my wife Patrizia and my daughter Daniela. Besides their continuous support and encouragement they also helped me, as potential target readers, providing useful suggestions on how to improve in many points the first draft of the manuscript.

Cesena,
December 2007 *Maurizio Gasperini*

Contents

1. Introduction

The past century has been characterized by ever-increasing progress in our knowledge of nature and our understanding of its physical laws. The experimental investigation of the properties of matter, starting from the development of atomic physics at the end of the nineteenth century, has allowed us to look inside the atom, inside its nucleus, and even inside the constituent particles of the nucleus, pushing the frontier towards ever-decreasing distances and ever-increasing energies. At the opposite scale, astronomical and astrophysical observations have allowed us to go beyond the frontiers of our solar system and our galaxy, and we have even broken free from every kind of optically active system, pushing the frontier towards ever-increasing distance scales and thereby exploring older and older epochs.

At the same time, the development of progressively more sophisticated theoretical and mathematical models such as relativity, quantum mechanics, and field theory, has allowed us to build up a coherent framework to accommodate and understand this vast amount of experimental data. The two paths laid down by the development of nuclear physics and astrophysics, apparently divergent (in distance scale) but effectively convergent towards ever-increasing energies, then successfully merged, yielding, during the 1970s, the so-called standard cosmological model. It is certainly not an overstatement to say that this model represents one of the pillars of twentieth-century physics.

The standard cosmological model, which will be described in detail in the following chapters, provides us with a complete and satisfactory description of the current Universe. Furthermore, this model can be extrapolated backward in time to recover the temporal evolution of the Universe – explaining for instance the origin of light elements (so-called nucleosynthesis), starting from an initial state characterized by a primordial hot "mixture" of elementary particles. Moreover, the natural completion of the standard model, known as the inflationary model, explains how the large scale structures that we currently observe (galaxies, clusters of galaxies) may emerge from tiny primordial fluctuations in the matter density.

According to the standard model and its "inflationary" extensions, the Universe is a system which has continously expanded from a huge initial explosion, commonly known as the Big Bang. The relics of this explosion (in particular, the cosmic microwave background, electromagnetic radiation characterized by a thermal, black-body spectrum) was first observed in 1965 by Arno Penzias and Robert Wilson, who were awarded the Nobel Prize for this discovery. Despite the fact that such results are relatively recent, the concept of the expanding Universe has already become part of popular culture. Indeed, expressions like "explosive Universe", "Big Bang", and "initial singularity" are now common language. There is widespread awareness that the Universe is "expanding". A number of excellent popular science books, written by world-renowned scientists, describe the history of the Universe from the Big Bang to the present time.[1]

But what exactly do we mean by the Big Bang?

As the term suggests, a Big Bang is certainly a big explosion. More precisely, a rather violent and fast production of radiation and matter particles characterized by extremely high density and temperature. The cooling produced by the expansion (according to the standard laws of thermodynamics) has "firmed up" such particles into matter lumps, that have eventually combined into the large scale structures of the Universe we observe today. We can say that these aspects of cosmological evolution are well understood and widely accepted, barring some still debated issues concerning, for instance, the problem of baryogenesis (i.e., the mechanism by which only matter particles are produced from the relics of the primordial explosion, while large lumps of antimatter seem to be completely absent today on large scales).

The term "Big Bang", however, is often used (even in a scientific context) in a broader sense, as synonymous with the birth and origin of the Universe as a whole. In other words, this term is used

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[1] See for instance S. Weinberg: *The First Three Minutes* (Basic Books, New York 1977).

also to indicate the single event from which everything (including space and time themselves) directly originated, emerging from an initial singular state, i.e., a state characterized by infinitely high values of energy, density and temperature.

This second interpretation is certainly suggestive, and even scientifically motivated within the standard cosmological model. Nonetheless, it has been challenged by recent developments in theoretical physics that took place at the end of the twentieth century.

Indeed, recent theoretical progress[2] suggest that the behavior of matter at very high energies could be radically different from what we usually observe in the ordinary macroscopic world. In particular, when the energy and the corresponding strength of the various forces are very close to a critical value – to be defined later in the book – it may no longer be legitimate to describe matter in terms of point-like particles (as suggested by the well established laws of low-energy physics). Matter could in fact take more "exotic" forms, either thread-like (called strings) or membrane-like, thus occupying spatial patches that progressively increase with energy. Furthermore, an even more astonishing consequence of this scenario – to be discussed in Chap. 10 – is that, as the energy and strength of the forces increase, the effective number of dimensions of space also rises. In other words, the dimensionality of space-time is not rigidly fixed, but becomes a *dynamical variable*.

These new theoretical ideas therefore suggest novel descriptions of the initial state of the Universe. Close to the Big Bang, i.e., in a regime of very high energy concentration, the state of the Universe was quite different not only from its current state, but probably also from the one predicted by the standard cosmological model. Besides being extremely hot and dense, and highly curved, the Universe was probably also a higher-dimensional structure, inhabited by exotic objects like strings and membranes, and dynamically governed by forces and symmetry laws that have left today only extremely weak (and possibly indirect) traces.

Within this scenario, more flexible and richer than the standard one, it becomes possible to build cosmological models without

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[2] See B. Green: *The Elegant Universe* (Vintage, London 1999) for a popular introduction.

any initial singularity, where cosmological evolution can be traced arbitrarily far back in time, even to infinity. Such models allow the Universe to exist, and develop through a long "prehistory", even before the actual Big Bang, now identified as the explosion which gives rise to the matter and to the forms of energy that we now observe. The Big Bang is still present but, although it remains a milestone in the evolution of the cosmos, no longer represents the origin of space, time, and the Universe itself. It thus becomes possible, within this framework, to explain *how* the Big Bang takes place, by studying mechanisms able to concentrate enough energy in a given space-time point to trigger the observed explosion.

All these aspects of modern cosmological models will be presented and illustrated – albeit in an incomplete fashion, if only due to lack of space – in the following chapters. But let us start by explaining how the hypothesis that the Big Bang was the origin of "everything", while having solid scientific roots, can nevertheless be challenged by recent developments in theoretical physics.

To this end, it is worth recalling one of the greatest lessons that the natural sciences have learned from Galileo, Newton, and the other founding fathers of modern physics: celestial bodies do not have any "mystic" essence or "metaphysical" property, but move and evolve in time according to the same laws that govern the dynamics of more mundane material objects. The whole Universe is itself an ordinary physical system obeying those laws that science seeks to discover and to piece together using reproducible experiments. The Universe that we observe today, in particular, can be fully (and satisfactorily) described on large scales by the laws of classical physics, including general relativity, the relativistic theory of gravitation developed by Albert Einstein at the beginning of the twentieth century. This theory both includes and generalizes Newton's gravitational theory, and has successfully passed all experimental tests performed since its conception.

As will be discussed in the next chapter, the theory of general relativity predicts a warping of space and time which is directly proportional to the energy density distributed in the matter sources. By applying this theory to our expanding Universe one then obtains a cosmological model in which the curvature of the Universe itself evolves with time, following the corresponding evolution of the energy density and temperature.

As the expansion proceeds, matter becomes progressively more rarefied and colder, according to standard thermodynamics. Thus, as a consequence of general relativity, the curvature of the Universe becomes gradually smaller. It is intuitively obvious, in particular, that an infinite expansion would tend to render the Universe completely empty, and its geometry – i.e., the space-time, to use relativistic jargon – would tend to become flat. In a similar fashion, one can use general relativity to establish that, in the past, when the Universe was smaller and more compact, it was also hotter, denser and thus much more warped than it is today. Going progressively backward in time the density, the temperature, and the curvature of the Universe increase without bound until they reach – in a long, but finite time interval – an infinitely dense, hot and curved "singular" state.

The idea that such a singular state (identified with the Big Bang, and conventionally placed at the time coordinate $t = 0$) may represent the birth of the Universe is based upon the fact that the dynamical equations of general relativity lose their validity at the onset of a singularity, and cannot be extended beyond a singular point (in this case, backward in time beyond $t = 0$). In other words, the solutions of those dynamical equations describe an "incomplete" space-time which is not infinitely extended in time, being characterized by an impassable "boundary" located at a finite temporal distance from any physical observer. It is thus general relativity itself which, in a cosmological scenario, unavoidably leads to the notion of an initial singularity, enforcing the idea that the Big Bang was the beginning of space-time and the moment of birth of our Universe.

If we were to adhere strictly to general relativistic predictions, we should then conclude that the main topic of this book – the Universe before the Big Bang – is something meaningless. Before jumping to this conclusion, however, there is a question we should ask ourselves. Is the incompleteness of space-time predicted by general relativity a true physical property of our Universe, or is it only a mathematical property of some equations, that are really inadequate to describe space and time near the Big Bang?

This is certainly a legitimate question in physics, where the occurrence of a singularity often does not correspond to any real entity, but is just a signal that some physical laws have been extrapolated beyond their realm of validity.

Let us consider the following, very simple and well-known example. The laws of classical electromagnetic theory establish that, inside the atom, the positively charged nucleus exerts an attractive force on the negatively charged electron, and that this mutual force increases as the distance between the two charged particles decreases (according to the well-known Coulomb law). In particular, when the distance between the nucleus and the electron tends to zero, the force becomes infinite. On the other hand, a revolving electron should progressively radiate away its energy, thus progressively shrinking its orbit closer and closer to the nucleus. We should then conclude that, according to the classical electromagnetic laws, all electrons would eventually fall into the nucleus, atoms would collapse into singular point-like states, and ordinary matter would not exist in the form we know it. Such a situation does not occur, however, simply because at short enough distances the laws of classical physics break down and the laws of quantum mechanics come into play, preventing the collapse of the electron into the nucleus.

We may also refer to another example, less obvious, but equally well known to physicists. The energy density of thermal radiation, computed by applying the laws of classical physics, obeys the so-called Rayleigh–Jeans spectrum. This predicts an unbounded growth of the energy density with the frequency of the thermal radiation. But once again this energy singularity disappears if we take into account the need to use quantum mechanics to describe the behavior of matter and radiation at high enough frequencies (i.e., at high enough energies). One then finds, by applying the required quantum mechanical principles, that the thermal energy density first increases with frequency, reaches a maximum at a finite frequency value, and eventually decreases as the frequency goes to infinity, following the so-called Planck spectrum (named after Max Planck, who was one of the founders of quantum mechanics).

There are also other circumstances, however, where the occurrence of a singularity in the equations describing a physical system may point to some abrupt change in the state of the system, requiring the introduction of different variables and different degrees of freedom for an appropriate description. In this case it is also instructive to consider a simple example, drawn from particle physics.

Let us first recall that at sufficiently low energies (i.e., well below the typical energy of strings) all known ordinary matter – including also those forms of matter produced artificially in the various accelerators around the world – can be reproduced by a proper combination of a relatively small number of fundamental building blocks, the so-called elementary particles. Some of these particles (actually, only a very small fraction of their total number) are stable: this means that, were they set up in a fully isolated environment, they would persist in their original state, retaining their physical properties unchanged for an infinitely long time. Other particles, however, are unstable: even without any external influence, these particles decay, that is, they disappear, leaving in their place two or more different (and lighter) particles. Their mean decay time, called the lifetime, depends upon the forces producing this intrinsic instability.

Consider, for instance, an atom. It consists of electrons (which are stable particles), protons (which are also stable, as far as we know) and neutrons, which are stable, but only within the atomic nucleus. In an empty environment (i.e., in vacuum) a neutron decays, with a typical lifetime of the order of fifteen minutes, producing three new stable particles: a proton, an electron, and a neutrino. Now for each of these "newly born" particles, the decay process can be regarded as a kind of "Big Bang" in the realm of subnuclear physics: an abrupt explosive process marking the appearance of these particles and the beginning of their life, on a microscopic scale. This does not imply, however, that these particles emerged from "nothing". Before they appeared, there was a corresponding physical system in a different initial state, representing a neutron which, under the influence of some nuclear forces (called weak interactions and first described theoretically by Enrico Fermi), has transformed into a new state represented by three different particles.

There is no doubt that the physical description of the system undergoes a sudden and abrupt change when the neutron decay occurs. Nonetheless, the decay itself does not represent any impassable boundary. In a similar fashion, the cosmological explosion that we identify as the Big Bang certainly marks the beginning of the present state of the Universe, i.e., of the Universe in the form that we currently observe. However, if we relax the a priori assumption that the Big Bang must also mark the origin of space and time, the question as to whether our Universe existed before such an explosive event, and in which state, may become perfectly meaningful.

An equally legitimate question, however, could also naturally arise at this point: Why should we address the issue about a possible state of the Universe before the Big Bang, thus casting doubts on the hypothesis – suggested and supported by general relativity – that the Big Bang is effectively the true beginning of everything?

The answer to this is quite simple. General relativity, as previously stressed, is a classical theory. It has been successfully tested at densities, temperatures and curvatures much higher than those we may observe in our ordinary macroscopic world, but definitely much lower than the ones coming into play in the primordial Universe. The use of general relativity near the Big Bang implies trusting the validity of this theory not only beyond any experimental evidence, but also in a regime where there are well-founded reasons for doubting the legitimacy of classical theories.

In fact, in the regime of extremely high energies, where the above-mentioned strings and membranes may become relevant, the properties of the gravitational interaction are expected to be significantly different from those predicted by general relativity. New fields and new kinds of short-range interactions may come into play, as inevitable consequences of the laws of quantum physics. On the other hand – as we shall see in the following chapters – it is the standard cosmological model itself that leads us to the unavoidable conclusion that quantum mechanics, together with the physical laws appropriate to describe matter on microscopic scales, are key elements in the dynamics of the primordial Universe.

Taking the expansion of the Universe seriously, and going backward in time, we do indeed reach epochs during which the entire structure of the Universe and its energy (currently spread over billions of galaxies) was compressed into a spatial region of about one hundredth of a millimeter in length. The energy density of the Universe at that time was inconceivably high compared to what we usually observe on macroscopic scales. We can compute, using general relativity, that the energy density for such a small compact region was about 10^{80} times greater than the typical density in an atomic nucleus (which is already very high). Such a value, dubbed the Planckian limiting density, is the threshold value corresponding to the onset of a regime where the geometry of space and time itself (together with matter) must obey the laws of quantum mechanics. General relativity, however, does not know about quantum mechanics: it can thus bring us to the doorstep of the Big Bang, so to speak, but it cannot proceed further without entering a regime in which its predictions are no longer reliable.

Therefore, in order to correctly describe the Universe when approaching the Planckian regime, a classical theory like general relativity is not sufficient. Instead one must have a theory able to provide a consistent description of gravitation even within a quantum framework. Since such a theory was not available when the standard model was developed, speculative attempts were made to extrapolate the predictions of general relativity right to its limits, that is, to describe the birth of the Universe from an infinitely hot, dense, and curved state: the initial singularity, beyond which nothing existed.

This methodology wherein the results of a known theory are extrapolated into an as yet unexplored range is a natural procedure after all, and it is common practice in the scientific context, as a first step towards more sophisticated theories and more complete models. However, as far as cosmology is concerned, pushing this procedure to its extreme leads us to identify the limits of our current knowledge with a natural barrier, as though nature had set up a definitive, impassable gate at the Big Bang position. Such a situation is reminiscent of the attitude the ancient peoples had towards the Columns of Hercules: since no-one had crossed the strait of Gibraltar, and no-one knew the world beyond it, it was common opinion (and it seemed plausible) that the world would end at that point.

This basic lack of knowledge, however, is continuously being filled by the recent developments of theoretical physics, which have provided us with a very powerful tool: string theory. In principle, this theory (and its possible, though as yet not fully defined completion, M-theory) allows a coherent merger of quantum mechanics and gravitation, and thefore provides a potentially consistent framework to describe the geometry of space-time in the regime of extremely high energy densities and curvatures. It has thus become possible to study the evolution of the Universe near the Big Bang, and even beyond it, by means of a robust and consistent theory, valid at all energies. It is as though, in the above analogy with ancient times, someone had built a more solid and reliable ship that would allow some brave explorers to sail the seas beyond the Columns of Hercules. In this way, it has been found that the extension of space-time is not necessarily constrained by an initial singularity, and questions about the possible state of the Universe before the Big Bang are fully legitimate and well posed.

Anticipating the demand of the curious reader, and as an introduction to the content of the following chapters, let us immediately give some idea of what the Universe would look like according to the indications provided by string theory, if we could look back in time to the epoch of the Big Bang, and even beyond the Big Bang itself. Such remote epochs cannot be traced using objects like stars and galaxies, which formed only very recently on the time-scale of cosmic evolution. These structures were not yet formed at the onset of the Big Bang, and neither did they exist before it. Instead, we need to exploit some geometrical properties of the Universe that are always valid, like space-time curvature. Let us therefore ask about the past evolution of space-time curvature, and represent its behavior graphically as a function of time.

According to the so-called standard cosmological model (which will be introduced in Chap. 2, and which is the model providing the grounds for the hypothesis of the Big Bang as the singular beginning of "everything") the Universe expands and the curvature decreases in time in a continuous and decelerating fashion. Hence, going backward in time, we reach epochs characterized by progressively increasing curvature. This monotonic growth proceeds continually until the infinite curvature state is reached (corresponding to a singularity, and conventionally fixed at the initial time $t = 0$). Beyond that point, no classical description is possible (see Fig. 1.1).

However, as already pointed out, a singularity can often be interpreted in a scientific context as a signal that we are applying

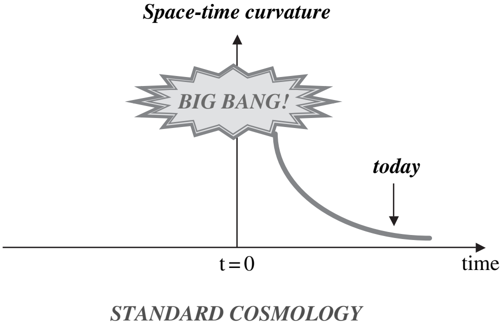

FIGURE 1.1 The *bold solid curve* describes the behavior of the curvature scale of our Universe as a function of time, according to the standard cosmological model. The further we go back in time, starting from the present epoch, the higher is the curvature, approaching infinity as t approaches zero. Thus $t = 0$ is identified with the moment of the Big Bang and the beginning of space-time itself

some physical laws outside their realm of validity. Concerning this point, it is interesting to quote the opinion of Alan Guth, one of the fathers of modern inflationary cosmology (a subject covered in Chap. 5). In his recent book[3] he makes the following remarks about the initial singularity:

> It is often said – in both popular-level books and in textbooks – that this singularity marks the beginning of time itself. Perhaps it's so, but any honest cosmologist would admit that our knowledge here is very shaky. The extrapolation to arbitrarily high temperatures takes us far beyond the physics that we understand, so there is no good reason to trust it. The true history of the universe, going back to "$t = 0$", remains a mystery that we are probably still far from unraveling.

In other words, according to Guth, there is little hope of describing the initial phase of the Universe within the standard cosmological model. Indeed, as we have already pointed out, in the presence of arbitrarily high curvature, energy and density, the Einstein theory of gravitation ceases to be valid, and the associated description of the space-time geometry becomes meaningless.

Beside the singularity problem, however, there are also other issues concerning the standard cosmological model that hint at the

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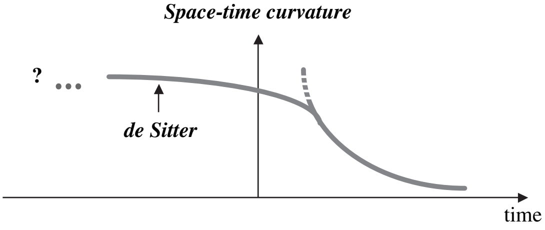
[3] A. Guth: *The Inflationary Universe* (Vintage, London, 1997), p. 87.

need for a modification near the initial time, even before reaching the quantum gravity regime. Such a modification requires in particular that, at some point during its primordial evolution, the Universe should undergo a phase of highly rapid expansion, dubbed inflation. We are giving here just a glimpse of what will be illustrated in more detail in Chap. 5. For the purposes of our fast-track, time-reversed journey, it will be enough to point out that during an inflationary phase of conventional type the evolution of the Universe is expected to be determined by the energy density of a "strange" particle – dubbed the inflaton – that generates a scalar-type field strength.

Going further backward in time, the potential energy of this field progressively increases, and eventually becomes so strong as to be able to "freeze out" the space-time curvature. Then, as shown in Fig. 1.2, the curvature of the Universe stops increasing and levels off to an almost constant value. During this initial inflationary phase, the geometry of the Universe thus approaches that of the de Sitter space-time (named after the cosmologist who found the solution describing a spacetime with constant curvature). The primordial Universe, in that case, closely resembles a tiny, four-dimensional hypersphere with constant radius.

However, there is also a problem in this case: a phase in which the Universe expands while the curvature stays fixed at a constant value cannot be extended backward in time without limit. In fact,



STANDARD INFLATION

FIGURE 1.2 The *bold solid curve* describes the behavior of the curvature scale of our Universe as a function of time according to the conventional inflationary model. When the Universe enters the inflationary regime the space-time curvature, instead of growing as predicted by the standard cosmological model (*dashed curve*), tends to become frozen at a constant value, asymptotically approaching a phase associated with a de Sitter geometry