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Excerpt
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Introduction

This is an account of the discovery and exploration of a sea of thermal radiation that smoothly fills space. The properties of this radiation (which we describe beginning on page 16) show that it is a fossil, a remnant from a time when our universe was denser and hotter and vastly simpler, a very nearly uniform sea of matter and radiation. The discovery of the radiation left from this early time is memorable because, as is often true of fossils, measurements of its properties give insights into the past. The study of this fossil radiation has proved to be exceedingly informative for cosmology, the study of how our universe expanded, cooled, and evolved to its present complicated condition.

The discovery of the fossil radiation grew out of a mix of lines of evidence that were sometimes misinterpreted or overlooked, and of ideas that were in some cases perceptive but ignored and in other cases misleading but entrenched. In the 1960s, it was at last generally recognized that the pieces might fit together and teach us something about the large-scale nature of the universe. We introduce the accounts of how this happened by explaining the lines of research that led up to the situation then. The story of what happened when the pieces were put together in the 1960s is told through the recollections of the people in the best position to know – those involved in the research. We have essays by most who took part in the recognition that this fossil exists, its properties may be measured, and what is measured may inform us about the nature of the physical universe. This did not happen all at once; nor was it done by a single person; nor was it always done knowingly. The collection of essays tell what happened in all the richness and complexity we suppose is typical of any activity that people take seriously.

The last part of this book describes how the developments in the 1960s led to the search and discovery of methods of accurate measurement of the properties of the fossil radiation and of methods of interpreting what is measured. This part of the story is told in a more orderly way – it is concerned with research directed to the solution of relatively well-posed problems – but it is no less rich. It shows how advances in technology and in the strategies of its application can dramatically increase our understanding of the world around us.

Look into the details of any other significant development in science and you are likely to find a story as rich and complicated as the discovery and exploration of the fossil radiation. Thus we offer this example of a particular advance of science as a lesson on the nature of the scientific enterprise. We can tell the story of the fossil radiation in finer detail than is usually done because this is a small slice of science, much of which played out not that long ago, with a relatively small number of actors. And because cosmology still is a relatively new science, it has not yet become exceedingly technical: we can explain the developments in words accessible to a nonspecialist who is willing to read carefully.[1] We believe this account is an instructive example for anyone who takes an interest in the nature of science and how it has led to our present understanding of the physical world.

The stories of search and discovery that scientists usually tell each other in books and scientific journals are much more schematic than what is presented here. Scientists as well as historians and sociologists complain about the distortions and simplifications that slight the wrong paths taken and understate the painstaking learning curves that experimentalists, observers, and theorists follow as they sometimes find better paths. But "tidied up" stories do serve a purpose in helping us keep track of the central ideas as well as reminding us that our subject does have a history. As a practical matter this is about the best scientists generally can do. Those who know what actually happened seldom are willing to take the time from research to tell it in detail; even if they did the rest of us would have little time to spare to read about it; and when we did we would find it difficult to pick out the threads that led to advances rather than dead ends. But it is important to have some examples that take the opposite tack: explore what happened in detail. This is our purpose in describing the discovery and exploration of the properties of the fossil radiation left from what we will term the "hot big bang."

The contributors to our set of recollections of what happened when the clues to the fossil radiation were put together in the 1960s have had a broad

[1] There are equations, for the pleasure of those who like them, but the equations that appear in the main text are not needed to understand the situation: the accompanying words are meant to convey the sense of the ideas. The more specialized mathematics and comments in footnotes and the Glossary are intended for specialists.

variety of careers. Some continued in this line of work after 1970, but many have gone on to other things. Some were led to work on cosmology, the study of the large-scale nature of the physical universe, by the elegance of the issues: does the world as we know it last forever, or if not does it end in fire or ice? Others were reluctant to get involved because the data one could bring to bear on such questions were so exceedingly limited. Some were drawn to cosmology by the challenge of making a particular measurement or calculation. Others became involved by accident, not realizing that their work would become important to the study of the expanding universe. We have descriptions of what it was like to be a student then, or to be further along into a career in science, along with accounts of how the contact with this subject shaped careers and lives.

Our set of recollections cannot be complete because some of the actors are no longer with us. That includes Yakov Zel'dovich, who led a research group in the USSR that came close to the discovery of the radiation and, after its discovery, contributed much to the exploration of its significance. We have also lost Francesco Melchiorri, a pioneer in the use of bolometers to measure the radiation. In the USA losses include George Gamow, Ralph Alpher, and Robert Herman. Their pioneering work in the 1940s and 1950s on the thermal properties of the early universe is central to the history related in Chapter 3. On the experimental side losses include Robert Dicke, Allan Blair, and David Wilkinson. Bob Dicke suggested that Wilkinson and Peter Roll search for this fossil radiation, using technology he had invented two decades earlier. Al Blair with colleagues at the Los Alamos National Scientific Laboratory was one of the pioneers in the measurement of the fossil radiation above the atmosphere. Dave Wilkinson, his colleagues and students, and in turn their students, have played a leading part in the measurements of the properties of the radiation, from the time of its discovery and continuing through to the two spectacularly successful satellite missions, Cosmic Background Explorer (COBE) and WMAP, which have given us precision measures that imply demanding constraints on the large-scale nature of the universe. In England we have lost the pioneers of the steady state cosmology, Fred Hoyle, Hermann Bondi, and Thomas Gold, and a close associate, Dennis Sciama. In the late 1960s Sciama became persuaded by the evidence for a hot big bang, while Hoyle continued to lead the spirited exploration of alternatives to the relativistic big bang cosmology. We do have recollections by close associates; they are a valuable part of the story.

We are saddened by the loss of two contributors to the collection of essays. Don Osterbrock, at the University of California in Santa Cruz, was among the first to recognize evidence that most of the helium in stars is a fossil from the early universe. This helium is closely related to the fossil radiation, but the observational indications are very different. Our explanation of his thinking commences on page 59; his recollections start on page 86. Ron Bracewell at Stanford University took an early lead in the development of the strategy for the measurements of the small departures from an exactly smooth sea of radiation. These measurements have proved to be exceedingly useful guides to how the concentrations of matter in galaxies and clusters of galaxies grew, in the process disturbing the radiation. His recollections begin on page 385. The technique he and his student Ned Conklin pioneered reappears in later generations of experiments. That is illustrated in Figure 5.6 on page 429. The recollections by our colleagues Don Osterbrock and Ron Bracewell, along with the other contributors to this volume, will edify generations to come.

Our guidance to contributors in the first round of invitations is summarized in the statement that

> We invite your account of personal experiences. What did you know then about cosmology and what did you think of it as a branch of physical science? What issues of research or lines of thought led you by plan or serendipity to be involved with the idea of a primeval fireball (as it was then called)? What were your reactions to the discovery of the radiation, and what effect did the discovery have on your research?

We have made no attempt at documentation in these recollections, which we suspect would have been sparse compared to the density and complexity of the set of essays. We might have done better by going into the field to add interviews to the essays, and maybe even digging through notes and letters, though none of that is a practical plan for us. Lightman and Brawer (1990), in *Origins: the Lives and Worlds of Modern Cosmologists*, interviewed several of the people who contributed to these essays, and their questions are similar to ours, though not confined to as narrow a range of time and topic. They had the advantage of being able to ask a series of questions. But one may respond differently in an interview than to an invitation to write an essay, and we think we see the difference in the comparisons of what people who appear here and in *Origins* have to say. An analog of the follow-up question in an interview is the sharing of recollections of dates and events by some of our contributors. Apart from gentle hints, and a few corrections of well-documented points, we have not contributed to this interaction, or otherwise attempted to enhance the content or coherence of the essays.

The essays are informed by a considerable variety of philosophies of the theory and practice of science. To this must be added the variety of what the contributors happened to be doing in the 1960s, what they later considered worth recording in this volume, and what they happen to remember or are able to recover from fragmentary records. But in our opinion these recollections are the best feasible basis for an understanding of what actually happened and why. In science one seeks significant patterns in complex situations. We hope the reader will enjoy the opportunity of applying this tradition to the set of essays.

The research in the 1960s on fossils from the big bang grew out of what had happened earlier. In Chapter 3 we trace the histories of ideas and methods of measurement from early developments in the 1940s up to the general recognition in the 1960s that one may put these ideas and methods together. Our account of the science before 1960 is selective: we pay particular attention to those developments in cosmology that have proved to be relevant to the interpretation of a fossil from the early hot stages of expansion of the universe, the sea of radiation, along with a related fossil, the lightest of the chemical elements. This chapter concludes with a broader assessment of the state of the theory and practice of cosmology in the early 1960s: the observations and ideas that were more widely discussed and those that might have merited closer attention.

Our account of events leading to the situation in the 1960s is presented in the standard style for scientists that we mentioned earlier: we almost exclusively report what appears in the published scientific literature of the time (with a few exceptions that we hope are clearly apparent), and we present the development of our subject as a generally linear and orderly advance of knowledge. That is not the whole story by any means: we have omitted wrong steps that no longer seem relevant and all the other rough places that the essays are meant to illustrate. But, as we have remarked, this linear presentation is a well-tested and efficient way to present the main elements of the science. And because cosmology up to the 1960s was a small science, and only a small portion of that was concerned with fossils from the early universe, we have the space to explore the more interesting of the steps we now see were in wrong directions. This is important: mistakes are an inevitable part of advances in the enterprise of science.

There was an interplay of theory and practice in the science of cosmology leading up to the 1960s, including the first steps to the modern theory taken in the 1920s. But the scant observational basis allowed considerable and perhaps even unhealthy room for speculation undisciplined by observation. Even in the 1960s it was not at all unreasonable to doubt the progress toward checking ideas by piecing together an empirically based theory of the physical universe from our limited view in space and time. An example is in the foreword to the book *General Relativity and Cosmology* by Robertson and Noonan (1968). In the foreword the physicist W. A. Fowler wrote "Within its limitations special relativity is faultless. Whether this be true of general relativity remains to be seen. Cosmology is mostly a dream of zealots who would oversimplify at the expense of deep understanding. Much remains to be done – experimentally, observationally and theoretically. *Relativity and Cosmology* – Robertson's legacy made manifest by Noonan – surveys the fruit of past endeavors and is an almanac for the harvests to come."

When Fowler wrote this sensible assessment of the hazards of the enterprise of cosmology in the 1960s he may have been aware of the detection of the sea of radiation we now know is a fossil. (The detection is noted in this book, on page 390, but there is no mention of its possible significance for cosmology.) But in the mid-1960s Fowler was skeptical of the proposal that the radiation is a fossil from the past rather than something produced by processes operating in the universe as it is now. He was right to be cautious, and he was right also to caution that the use of Einstein's general relativity theory to describe the large-scale nature of the universe is an enormous extrapolation from the tests of this theory. At the time, experimental tests of general relativity were not very demanding, even on the length scale of the Solar System. If the observational and experimental basis for cosmology were as schematic now as it was in the 1960s, the discovery of the sea of radiation still would be an interesting development, but perhaps much less important to science than it has proved to be. That is because the measured properties of this radiation are a considerable part of the suite of evidence that now tightly constrains ideas about the large-scale nature of the universe, including stringent tests of aspects of general relativity theory applied on the enormous scales of cosmology. Fowler gave an accurate prediction of the present situation: much has been done, and it has yielded a rich harvest.

The counterpoint to the confusion of research on the frontiers of science is the development of webs of evidence that can become so tightly and thoroughly crosschecked that we can be confident they are good approximations to aspects of objective physical reality.[2] Chapter 5 shows an example of how an interesting issue, here the interpretation of the sea of radiation, can drive the development of new methods of measurement that build on earlier

[2] It is worth pausing to consider what is meant by this sentence. Research in physical science has made enormous progress by operating under the assumption that there is an objective physical reality that operates by rules we can discover, in successively improved approximations. The great advances of science reinforce the assumption: this is not an issue scientists generally consider worth discussing. The reality defined this way does evolve, of course. In quantum physics an isolated system may be in a definite state that does not have a real and definite energy until isolation is broken and a measurement forces the system to a real energy level. Here the older notion of reality is abandoned; we have a better approximation. The cosmology we are discussing is a physical science that operates by the standard and established conventions, including the highly productive working assumption of an objective physical reality, whose definition may evolve as we learn what questions we should be asking.

experience and teach us new things about the world around us. As experimentalists learned how to overcome the many obstacles to the spectacular precision of later measurements of the fossil radiation, they in turn drove theorists along their own learning curves on how to characterize the universe the measurements were revealing. The theoretical side of cosmology is guided by ideas of elegance, as is true of all physical science. But our ideas of elegance are informed by what observations and experiments teach us, and the ideas in turn inspire new observations.

By the beginning of the 21st century, at the time of writing this book, the interplay of theory and practice had produced a cosmology that passes a demanding network of experimental and observational tests. It is not practical to tell how this happened in the detail we could devote to the developments in the 1960s: too many people were making key contributions to too many lines of evidence. In Chapter 5 we return to the less realistic but more efficient linear style of presentation of Chapter 3 in describing what has been learned from precision measurements of the energy distribution of the fossil radiation and of the nature of its spatial distribution. This is supplemented by a tabulation in the Appendix of the series of experiments by which people learned how to make the measurements that so usefully characterize the radiation. A full account of how cosmology grew into the well-established science of the early 21st century would require tracing developments of other lines of evidence, some of which predate the idea of a hot big bang. We offer only the very condensed summary of this other work in Section 5.4. The course we have chosen leaves room instead for a closer study of how the science of the microwave radiation was done.

We have tried to make this worked example of science accessible to interested nonspecialists. We begin in the next chapter with explanations of the basic concepts of the established cosmology: what is meant by an expanding universe and a hot big bang, what can be said about the contents of the universe, and how the contents affect the history of its expansion. As we have mentioned, there are equations, but the text is meant to convey the sense of the discussion. The Glossary gives definitions of the jargon that appears in the essays and, inevitably, in the introductory and concluding chapters. The Glossary also is meant to serve as a guide to the somewhat complicated relations among ideas and issues. We offer references to the scientific literature for those who want to get into the really technical details. The citations are by the names of the authors and the date of publication, and the references to the literature are listed in the bibliography at the end of the book. The page numbers at the end of each reference in the bibliography serve as a supplementary index.

A gentler but still authoritative introduction to cosmology is in Steven Weinberg's (1977) *The First Three Minutes*. Helge Kragh's (1996) *Cosmology and Controversy* is a broader survey of the rich history of research in cosmology, and it is based on a broader variety of sources. We think of Kragh's style as intermediate between our more narrowly focused presentations in Chapters 2 and 3 and the full-blown details and complex panorama of recollections in the essays in Chapter 4. The reader will find that the essays are not fully concordant with these other accounts, careful though they are, or even with each other. Human events are complicated, and we have not sought to enforce a single vision of this example of research. Experts may find much of the science familiar, but unless they have long memories they would be well advised to look over Chapter 3, because the situation in cosmology in the early 1960s was very different from what grew out of it.

2

A guide to modern cosmology

The universe is observed to be close to uniform – homogeneous and isotropic – in the large-scale average.[1] That means we see no preferred center and no edge to the distribution of matter and radiation, and what we see looks very much the same in any direction. Stars are concentrated in galaxies, such as our Milky Way. The galaxies are distributed in a clumpy fashion that approaches homogeneity in the average over scales larger than about 30 megaparsecs (30 Mpc, or about 100 million light years, or roughly 1 percent of the distance to the furthest observable galaxies).

Space between the stars and galaxies is filled with a sea of electromagnetic radiation with peak intensity at a few millimeters wavelength and with spectrum – the energy at each wavelength – characteristic of radiation that has relaxed to thermal equilibrium at a definite temperature, in this case $T = 2.725\,\mathrm{K}$. This thermal radiation is much more smoothly distributed than the stars, but its temperature does vary slightly across the sky.[2] (The temperature differs by a few parts in 100,000 at positions in the sky that are separated by a few degrees.) The evidence developed in this book is that the radiation is a fossil remnant from a time when our expanding universe was much denser and hotter, and that the slight temperature variations were caused by the gravitational pull on the radiation by the increasingly clumpy distribution of matter in galaxies and clusters of galaxies.

We offer in this chapter a guide to basic ideas behind the interpretation of the radiation. We begin by explaining the concept of a universe that

[1] This situation is termed the "cosmological principle." It is an assumption that Einstein (1917) introduced and is now observationally well supported.

[2] The distributions of mass and this thermal radiation are seen to be close to homogeneous by the special class of "comoving" observers who are at rest relative to the mean motion of the matter and radiation around them. An observer moving with respect to this frame sees gradients in the distributions of matter and radiation. This definition of a preferred motion is not a violation of relativity theory, which of course allows observation of relative motion, here relative to the comoving rest frame defined by the contents of the universe.

is homogeneous and expanding in a homogeneous and isotropic way. Section 2.2 describes the meaning of thermal radiation and its behavior in this expanding universe. In the concluding section we present a list of the main known forms of matter and radiation in the universe as it is now. This inventory figures in the analysis of the properties of fossil remnants from the early stages of expansion of the universe: the thermal radiation and isotopes of the light chemical elements. The origins of ideas about these fossils in the 1960s are described in Chapter 3 and in the essays in Chapter 4.

2.1 The expanding universe

The expansion of the universe means that the average distance between galaxies is increasing. Figure 2.1 shows an early use of a model that helps illustrate the situation. Imagine you live in only two spatial dimensions on the surface of a balloon. Do not ask what is inside or outside the surface – you are confined to your two-dimensional space on the rubber sheet of the balloon. In your two-dimensional space you see a uniform distribution of galaxies: there may be local clustering, as we observe in the real universe, but the mean number of galaxies per unit volume (which in this example is an area) is the same everywhere. As the balloon is blown up the galaxies move apart. Another caution is in order here: the galaxies themselves are not expanding. An observer at rest in any galaxy sees that the other galaxies are moving away, at the same rate in all directions, as if the observer were at the center of expansion of this model universe. But an observer in any

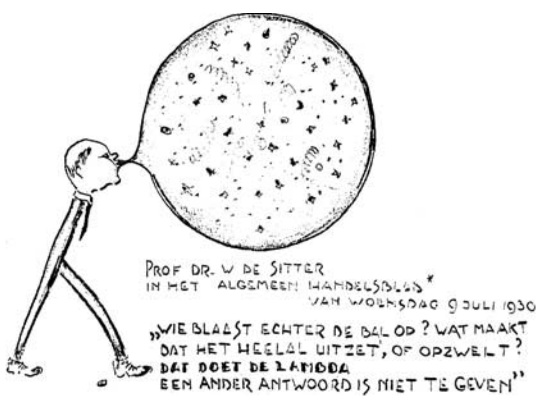

Fig. 2.1. A sketch of Willem de Sitter on the occasion of his explanation of the idea of an expanding universe in a Dutch newspaper in 1930. His body is sketched as the Greek symbol lambda, or λ, which represents Einstein's cosmological constant. As will be discussed, this constant was taken seriously then and came back into fashion.