Thomas Sanford

A Whirlwind History of the Universe and Mankind

From the Big Bang to the Higgs Boson

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To my Father
F. Bruce Sanford
my early teacher who
showed me the beauty
of science

and

To my later guide
Leon M. Lederman
who taught by example

Preface

This book is written for the person who is curious about how we humans came to be here and who is interested in understanding a little of the science and social evolution that enabled us to affirm that a Big Bang actually happened and for the need of a Higgs Boson.

The text emphasizes, where possible, the why behind various evolutionary plateaus, from the universe's beginning in the Big Bang, to the visible heavens, our solar system and to Earth, with its evolution of life. From the emergence of Homo sapiens and the agricultural revolution, the discussed history narrows from that of the early Middle East, to the development of the Mediterranean civilizations, including Greece and Rome, to the European Renaissance, the English industrial revolution, and to the early European science discoveries, particularly those in physics. This path, through to the American Manhattan Project, leads to the exploration of what is inside the nucleus in the new field of high-energy particle physics. It is this road, which gave rise to theorizing the existence of the mass-giving Higgs boson and then discovering it, that is articulated; all condensed in less than 200 pages and fulfilling the book's title.

In the book's beginning, known science is used to explain the evolution from the Big Bang. Later, as Homo sapiens became humans and society developed, this early history and eventually the science that evolved the physics necessary to understand the beginnings is explained historically. Only the present scientific consensus from a microsecond after the Big Bang is discussed. Prior to the Big Bang, no understanding based on science is known to the author nor is commented on. A summary of the major events, during each of the three time periods discussed (beginnings, humans, and physics), is included as a time-line in the Key Events Discussed. References consulted are listed in the Bibliography at the end of the book.

In the text, a few equations are used to illustrate the concepts being discussed. These are there to illustrate the innate beauty and simplicity of the ideas behind the words. The equations are easily skipped without loss of understanding of that which is written. Although the book is meant to be read as a whole, the material covered is vast. However, each of the chapters is self-contained and can be read as a unit without loss of comprehension.

To assist in guiding understanding of the unfamiliar places mentioned, insightful maps are easily available on the Web, which the author suggests using. Similarly, technical terms are occasionally used in the various areas of science discussed and these are also quickly explained by referring to the Web.

Credibility to that which is written is given by the author's eight years of research in high-energy particle physics at both the Nevis (Columbia University) and Brookhaven National Laboratories in the USA, seven years at the Rutherford High-Energy Laboratory in England and CERN (French: *Conseil European pour la Research Nucleaire*), Laboratory in Switzerland, his nearly two decades of research into pulsed power technology and nuclear fusion as a Distinguished Member of Technical Staff at the Sandia National Laboratories in NM and his travels throughout the regions discussed (except that of Iran and Iraq). In 1973, the author received his Ph.D. under Nobel Laureate Leon M. Lederman. In 2000, he became a fellow in the American Physical Society, and in 2005, he received the Hannes Alfven Prize by the European Physical Society. He is the lead author on 60 of 102 journal publications and author or contributor to 281 technical articles. A short summary of his science background can be found in the author's *History of HERMES III Diode to Z-Pinch Breakthrough and Beyond (learning about Pulsed Power and Z-Pinch ICF)*, published by Sandia National Laboratories as SAND2013-2481, April 2013, and available on the Web.

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Contents

Abbreviations

AGS	Alternating Gradient Synchrotron
BNL	Brookhaven National Laboratory
CERN	French: *Conseil European pour la Research Nucleaire* (European Council for Nuclear Research)
CGS	Centimeters, Grams, Seconds
CMB	Cosmic Microwave Background
CNTBT	Comprehensive Nuclear-Test-Ban Treaty
COBE	Cosmic Background Explorer satellite
CP	Charge Parity
CPT	Charge Parity Time
DESY	Deutsches Elektronen-Synchrotron
DNA	Deoxyribonucleic Acid
DORIS	Eelectron-Positron Collider at DESY
GPS	Global Positioning System
GTR	General Theory of Relativity
HEP	High-Energy Particle Physics
IBM	International Business Machines
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
MCS	Multiple Coulomb Scattering
MIT	Massachusetts Institute of Technology
MKS	Meter, Kilogram, Second
NAL	National Accelerator Laboratory
NASA	National Aeronautics and Space Administration
PETRA	Positron-Elektron-Tandem-Ring-Anlage Collider at DESY
PS	Proton Synchrotron
PTBT	The Partial Test Ban Treaty
QED	Quantum Electrodynamics
RCO	Roman Climate Optimum
RNA	Ribonucleic Acid

SLAC	Stanford Linear Accelerator Center
SM	Standard Model of Particle Physics
SPEAR	Positron-Electron-Asymmetric-Ring
SPQR	Senatus Populusque Romanus
SPS	Super Proton Synchrotron
STR	Special Theory of Relativity
USA	United States of America

Part I
Beginnings

Chapter 1
Introduction

Amazingly, our universe had a birthday 13.7 billion years ago (BYA). Amazingly, we have a credible scientific explanation of how we have come to know this. And, even more amazingly, we live in a time that enables us to tell this story.

This book provides a brief timeline of many of the key events between the universe's birth, now referred to as the Big Bang, and the recent discovery of the Higgs boson. Interaction with the boson's quantum field gives mass to us all, providing credibility to the physics of the Big Bang itself.

A century ago the known universe consisted solely of the Milky Way galaxy, the Sun and our planets. Only in 1929, did Edwin Hubble (1889–1953), using the new Mount Wilson telescope, discover that our Milky Way was not alone in the universe but was one of billions of other galaxies. Moreover, these other galaxies were all moving away from the Earth. The farther away these galaxies were, the faster they moved, as if they originated in a Big Bang. But it was not until 1960, when the Cosmic Microwave Background (CMB) predicted by Big Bang theories was accidentally observed, that scientists believed an actual Big Bang had occurred. It was only then that the Big Bang was taken seriously.

The identification of the Big Bang less than 100 years ago was just one of a series of discoveries that have altered our understanding of the world in which we live. Examples of other dramatic and relatively recent scientific discoveries are the following:

- DNA—the basis of life—was discovered in 1953.
- Plate tectonics—the movement of continents—was verified in 1960.
- Tiktaalik—the link between fish and quadrupeds like ourselves—was found in 2004.
- The Higgs boson—which gives all of us, including the world, mass—was discovered in 2012.
- Gravity waves—from the collision of two black holes—was observed in 2015.
- An actual image—of a black hole—was constructed from its surroundings in 2019.

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The formation of a black hole is like an inverse of the Big Bang in that all matter within its vicinity is gravitationally sucked into its interior and turned back into energy. No light is ever able to escape.

Such fundamental observations, together with an increasingly detailed historical record, makes it possible to provide a relatively complete story of how we came to be who we are. Human social development, with its collective learning, and the concurrent evolution of the sciences, with its associated technologies, have been essential in enabling this understanding.

Much of this knowledge is summarized in books known as *Big History.* Many contain beautiful illustrations and explanations that describe the sequence of events that have occurred throughout the world and that have led to today's awareness. An excellent example of this approach is David Christian's *Maps of Time: An Introduction to Big History,* published 2005 and his expanded book *Big History Between Nothing and Everything,* published 2014, together with two coauthors.

Motivated by a similar perspective, the author of this book focuses here on the science and the relevant social and cultural history. The book limits itself to developments in the West, where science and technology first took root. By keeping the discussion centered, this approach generates a historical timeline that can be understood and retained. To make the discussion plausible, as well as interesting, a sufficient amount of detail is included.

To achieve these goals, the book is separated into three parts and fourteen chapters. Part I discusses the generation of the physical universe from a millisecond after the Big Bang and is referred to as BEGINNINGS. It includes the formation of galaxies, stars, the Earth and the evolution of early life on Earth. Part II, HUMANS, begins when the first hominins evolved into Homo sapiens and developed social structures leading to the development of science. It includes the agricultural revolution, early city-states in the Middle East, empires in the Mediterranean Basin, in particular, Greece and Rome, and the formation of the European states to the French revolution. Part III, PHYSICS, includes the development of Western physics in the eighteenth through twentieth centuries. These chapters discuss the historical understanding of the basic constituents of matter formed during the Big Bang, thereby providing credence to the model for the Big Bang itself. The book closes with the discovery of the Higgs boson, whose quantum field gives mass to ourselves and the universe.

Chapter 2
Matter Universe

Early Big Bang

Extrapolating the measured mass density of the universe to near a time when the universe's mass converged 13.7 BYA, suggests temperatures and densities reached unimaginably high values. Extrapolation of the radiation (photon) density of the universe to this time indicates that the radiation-energy density dominated the mass-energy density in an explosive fire ball.

Within a microsecond of this beginning, as the universe continued to expand and cool, the mass density and temperatures decreased to conditions that are now studied in particle accelerators. These studies suggest that a millisecond after the Big Bang, mass in the form of quarks and leptons, and the force carrying particles, bosons, were easily produced from the radiation itself. The lowest mass leptons are the electron and neutrinos. The Higgs boson gives particles their mass through interaction with its associated quantum field. Typical processes included pair production, where collision of two photons generates a particle and an antiparticle pair. The result was the formation of a plasma sea of quarks, leptons and bosons within a radiation field of photons. (The unfamiliar terms, such as plasma, quarks, leptons, neutrinos, etc., are all explained in detail in later sections of the book as their discovery and development evolved historically.)

As this plasma continued to cool, the quarks bound together to form numerous elementary particles, which themselves decayed into other elementary particles and radiation. After 1–100 s had elapsed, the only discrete particles remaining were the protons (formed from two up and one down quark), neutrons (formed from one up quark and two down quarks), electrons, neutrinos and the ever present Higgs field.

At this time, the neutrons and protons were in thermal equilibrium, converting back and forth into one another through a weak nuclear processes; as in electron-proton collisions, which form a neutron and neutrino, and vice versa. Because a neutron weighs more than a proton and electron combined, more energy is required to make the conversion from proton to neutron than vice versa. Thus, as the universe

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continued expanding and cooling, the number of energetic electrons needed to make the conversion decreased.

Approximately one second after the Big Bang, the rates of conversion became too slow to keep up with the expansion, so the proton-to-neutron conversion stopped. An isolated neutron is unstable and decays into a proton, electron and neutrino with a lifetime of fifteen minutes in a process referred to as nuclear beta decay.

Initially, there were enough neutrons to make the isotopes of hydrogen nuclei: deuterium, which contains one neutron and one proton, and tritium, which contains two neutrons and one proton. Eventually, nuclei of helium, containing two bound protons, and a tiny amount of lithium, which contains three bound protons, were produced through the process of nuclear fusion. By about three minutes, however, the excess neutrons were used up before elements with higher numbers of protons in their nucleus could be made.

Protons are the nuclei of hydrogen. Today, this simplest form of matter comprises 70% of all stable observable matter in the Universe, while helium accounts for 27%. The higher atomic-number elements, which now constitute the remaining 3%, appeared later, during the formation of stars. Neutrons are required to stabilize such nuclei. The strong force, which binds the nuclei of elements together, becomes overwhelmed by the repulsive electromagnetic force created by the addition of positive protons to the nucleus, during the short-time available for nuclear fusion to take place.

During this early time, radiation dominated over matter. As soon as the nuclei tried to form atoms with the available electrons, the fierce radiation field destroyed them. The cosmos remained a randomized and structureless plasma in which the radiation and matter were in equilibrium with one another.

As the universe continued expanding and cooling, the radiation-energy density decreased faster than the mass-energy density. Eventually, more than a thousand years after the Big Bang, nuclei began to attract electrons and formed atoms. The electromagnetic force between the positive protons and negative electrons pulled them together. The decreasing energy of the radiation no longer had the strength to break the atoms apart. At this time, matter emerged as the principal component of the Universe. Radiation decoupled from matter and the universe became nearly transparent, with most photons traveling unhindered through space. This transition occurred when the universe reached an age of approximately 0.5 million years (MY) after the Big Bang.

This radiation cooled and its wavelength was red shifted (stretched) as the universe continued expanding. Today, it is detectable as the cosmic microwave background (CMB) radiation, which fills the universe around us as an ancient hold-over from the Big Bang. It's spectrum agrees precisely with that expected from a blackbody radiation source, which is defined as radiation that has been thoroughly randomized and is in thermal equilibrium with its environment. This assumption of homogeneity and near isotropy is a key component in the Big Bang modeling and gives credence to the model itself.

Summarizing, the recession of the galaxies suggested that at some past time the universe began as a compact, hot, expanding entity. The observation of the CMB radiation, having a measured blackbody spectrum, was the most compelling and supporting evidence for the Big Bang. The CMB radiation relied on a different set of physical processes for its explanation than did the cosmological explosion theory for the Big Bang.

Additionally, the measured abundance of hydrogen and helium, with little else in the present universe, independently supports the Big Bang model. The universe cooled so fast, during its early expansion, that little time was available for all but the simplest nuclei to form. Moreover, no object in the universe has been found to be older than 13.7 billion years. Telescopes that observe the universe, as it was 10 billion years ago, show the early universe looked different than the universe appears today. That early universe was more crowded and contained objects like quasars that are now rare. A quasar (quasi stellar radio source) is a distant system powered by a super massive black hole billions of times more massive than our sun. Accordingly, the universe is not in a steady state but rather has changed significantly over time. This observational evidence strongly supports the Big Bang model. The Big Bang generated the space, time, energy and matter world in which we live today. Galaxies, stars and our Earth formed from this early homogeneous cosmos.

Galaxy Evolution

Once hydrogen and helium atoms dominated the universe, the electrically neutral cosmos continued to expand. As it spread over the next few hundred million years, radiation cooling continued. As a result, the universe became virtually dark. No stars existed.

Although the initial radiation density was remarkably symmetric, as indicated by the CMB data, it was not perfect. Variations at the level of one part in a hundred thousand occurred. Estimations suggest that this tiny variation was all that was needed to seed the formation of mass structures. Because this gravitational attraction between regions that have more mass is stronger, atomic matter began clumping together into giant clouds with empty space between these clusters.

Where more matter was present, gravity continued to coalesce adjacent matter. This motion continued within the giant clouds, even as smaller clouds of atomic matter formed. Approximately 700 million years after the Big Bang, the largest clumps formed protogalaxies with the smaller clumps of atomic matter heating as they collapsed in upon themselves. This heat energized the atoms, forcing them to move more rapidly, which led to frequent, violent collisions. Eventually the heat became so intense that the electrons were stripped from the protons, creating ionized plasma, which resembled the plasma of the early universe, except that it was gathered into discrete clumps.

When temperatures of 10 million degrees were reached, the protons collided with enough momentum that they combined, forming helium through the process of nuclear fusion. During this conversion, mass was lost and converted into vast amounts of energy. The subsequent heat generated at the center of each collapsing cloud stabilized it, preventing the cloud from collapsing further. Thus, a star was born.

This process of energy formation and collapse was continuously repeated as smaller collapsing clouds of matter created billions of stars. In time, galaxies filled with stars, lighting up the universe. Each star generated heat and light as long as it had enough hydrogen to keep the fusion reactions going. Our galaxy, the Milky Way and our Sun, within the Milky Way, was formed in the same manner. In approximately 4.6 BYA our Sun was created. Today, the Sun is half-way through its life of 9–10 billion years.

For perspective, the number of galaxies in the observable universe is estimated to be about two trillion (2×10^{12}). The number of stars in the Milky Way is approximately 100 thousand million (10^{11}). The spiral structure of the Milky Way has a diameter of 106,000 light years (the distance light travels in a year). And our Sun is located about 26,000 light years from the galactic center on one of its spiral arms.

Two observations deserve mentioning before continuing: that of dark matter and dark energy. Dark matter is the additional mass needed to explain the rotation of the outer regions of galaxies. It also causes light to bend around large galaxies. In contrast, dark energy makes itself known by the finding that the most distant objects in the observable universe are receding at ever-faster rates. At present, understanding both dark matter and dark energy are active areas of research. Both operate on galactic scales and neither affects what happens on Earth.

Star Evolution

In general, a star first uses its supply of hydrogen in its core to produce helium through nuclear fusion. The next phase in its evolution depends critically on the star's initial mass. If the star's mass is small, it soon runs out of hydrogen, the core fills with the helium byproduct and fusion ceases. Without heat from the fusion process, the core collapses due to its compression from gravity. Its center heats up expelling its outer layers into nearby space. It is now called a white dwarf and becomes even smaller. Yet, because of the intense heat remaining in its core, it continues radiating as its heat slowly dissipates. Once cooled, the star eventually evolves into a cold, inert and burned-out mass. What was once a glowing star is now referred to as a black dwarf.

If the star has more mass, like our Sun, temperatures rise high enough in its outer layers for hydrogen fusion to continue. As a result, the star expands forming a red giant. In such stars, the collapse of the center creates temperatures high enough that helium fuses to form carbon. After the star depletes its helium, the core collapses. When our Sun reaches this point, present astrophysical theories suggest that it will expand until it engulfs the three nearest planets: Mercury, Venus and Earth. Carbon will then disperse throughout the nearby space before the Sun collapses in on itself and becomes a white dwarf. This will start to happen, in another few billion years.

More massive stars present a different physical dynamic. If there is more mass when they run out of helium, their cores will continue to collapse and the additional compression results in ever higher temperatures. In a sequence of volatile burns, the carbon fuses and creates other elements, such as oxygen and silicon. This order repeats as each new element is depleted. The core contracts, temperatures rise to even higher levels and the star continues to produce higher atomic-number elements. This process is structured, with different fuels being fused in different layers within the star.

Eventually, if the star is massive enough, its core reaches temperatures of 4 billion degrees Celsius and iron is created. Iron is the highest atomic-number element that can be made through the process of fusion. Once the core of a massive star has filled with iron and fusion ceases, the star collapses one last time in a massive explosion, called a supernova. Momentarily, the star shines as brightly as an entire galaxy, with most of its mass blown into outer space, forming an outward expanding ring around its remaining center.

In the explosion, enough neutrons are generated to produce the bulk of the higher atomic-number elements beyond iron in the universe. These elements need additional neutrons in their nuclei to maintain electromagnetic stability. They are not made in the previous fusion sequence. Rather, they are formed by a process of neutron capture from the exploding neutrons. Today, the Crab Nebula is an example of such a supernova. It exploded in 1051.

In time, the core of a supernova will further collapse into a dense compact mass. Depending on the star's mass, either a neutron star or a more massive black hole will be formed. A neutron star is generated when the pressures in the core of the star, become so intense that its electrons and protons merge to form neutrons. Due to its spin, it radiates electromagnetic energy in pulse rates that can be as fast as a few per milli-second or as slow as a few per second, and is referred to as a pulsar. These stars were first discovered in 1967. At the center of the Crab Nebula, for example, is a pulsar.

In 2017, two neutron stars were observed to engage and then collide. Like the explosion of a supernova, this merger produced copious amounts of heavy elements. It is now theorized that as many as half of the elements heavier than iron are produced by such collisions.

If the original star is even more massive, it can form a back hole, which is a region of space so dense that nothing can escape its gravitational field, not even light. Hence, its name. Astronomers have observed that our Milky Way has a large black hole in its center, as do most galaxies.

The first observation of black holes occurred in 2015, when the merger of two black holes was seen simultaneously by both of LIGO's (Laser Interferometer Gravitational-wave Observatory) interferometers. The LIGO "observatory" consists of two identical and widely separated interferometers situated in sparsely populated and out-of-the way places. LIGO Hanford in southeastern Washington State is in an arid shrub-steppe region crisscrossed by hundreds of layers of ancient lava flows and LIGO Livingston is 3002 km away in a vast, humid, loblolly pine forest east of Baton Rouge, Louisiana.

In 2017, LIGO detected the merger of two neutron stars. Both the black holes and the neutron star mergers were sensed in LIGO, by measuring the distortion