"Emiliani's book is truly encyclopedic, as it deals with everything, or almost everything, from quantum theory to Hitler's racist rantings. There are tables of physical and chemical data, summaries of great scientific discoveries, potted biographies of several hundred of the world's greatest scientists, jokes, cartoons, and a great deal of solid erudition on cosmology, physics, chemistry, geology, oceanography, evolution and environment... the book is undoubtedly a tour de force for a single author... There is no doubt that if students were to work through from beginning to end, absorbing all the lucid explanations of relativity, quantum theory and vector algebra, and solving all the problems posed in 'Think' pieces that conclude chapters, they would end up as formidable, well-equipped scientists, capable of dealing with almost any problem in Earth sciences."

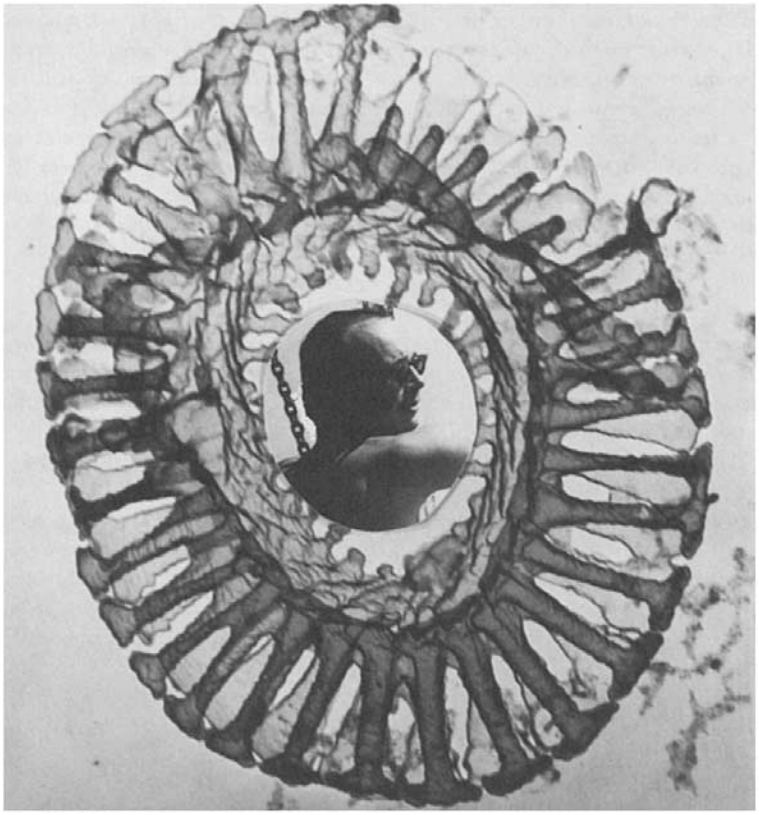
-Peter Francis, Geology Today

"...a charming, humorous, and entertaining book. Planet Earth *is ambitious, encompassing geology and most other Earth sciences as well as relevant aspects of physics, chemistry, and mathematics...that greatest of rarities among scientific treaties: it is comprehensive, informative, and best of all enjoyable."*

-Graham R. Thompson, Journal of Geological Education

"The book is admirable in its breadth...clearly and humorously written in a sympathetic style. I particularly liked the sections labelled THINK, when the reader is encouraged critically to examine preceding statements or to do a calculation or two. The text is clear and well written. The figures are generally very good and will provide useful illustrations for many lectures."

-Philip Kearey, The Times Higher Education Supplement



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The photograph shows the author encapsulated in a coccolith produced by *Emiliania huxleyi*, a coccolithophorid widespread in all oceans that was named after him.

Planet Earth

PLANET EARTH

Cosmology, Geology, and the Evolution of Life and Environment

Cesare Emiliani

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PREFACE

Our planet is at risk. The current explosion in the human population is forcing us to a simple but pivotal choice: stabilize the planet or perish. The first few decades of the next century will bring grave crises—environmental, economic, human. Only if we achieve a close understanding of the system of which we are part—how it came about and how it works—will the next generation be positioned to cope with the emerging problems.

Fortunately, the spectacular advances that have been made in many fields of science since World War II—in particle physics (quantum electrodynamics, the quark theory), in cosmology (the Big Bang, element formation, quasars, pulsars, black holes), in biology (the genetic code), and in geology (plate tectonics)—now make it possible, for the first time in history, to construct a model of the events from the Big Bang to today, a model that explains quite clearly how the Earth and life work. This achievement culminates 25 centuries of groping by the best thinkers and experimenters that humanity has produced.

Having a model does not mean that we know the ultimate truth—it only means that things *could be* that way or *could have gone* that way. Half a century ago, even such simple questions as "Why does the Sun shine?", "Why do children resemble their parents?", "How come are there so many volcanoes and earthquakes around the Pacific?" could not be answered. Today we either know the answer or have well-founded theories to explain the observations.

Our model demonstrates the unity of science. Cosmology is intimately connected to physics, and so are many areas of geology. Biology is related to paleontology, which documents the evolution of life on Earth. The motions of the Earth in space have timed the ice ages, which in turn have timed the evolution of the genus *Homo*. The examples that could be cited to demonstrate the close relationships of the various areas of science are truly innumerable. The common thread is, of course, mathematics—logarithmic expressions describe the timing of radioactive decay, which is the heart of the geological time scale; conic sections describe the paths of celestial bodies; forces, ubiquitous in the universe, relate to the second derivative of position with respect to time; the number e is at the core of growth and decay functions and of population dynamics.

There is much talk nowadays about the poor educational preparation of the present generation of students and the alarming level of science illiteracy at all levels of society. Much of the blame lies with the fragmentary way science is taught in the schools and is presented to the public in print and on television. It is as though an art lover had to be content to examine the Mona Lisa square inch by square inch, in no particular order, and across many months or years. How much would that person grasp of the meaning and aesthetic unity of the painting? How much does the average person grasp of the meaning and aesthetic unity of the universe? Very little, at best.

The media bear some blame, too, seeing that only one percent of the books reviewed by the leading newspapers and magazines are science books. Even though the venerable *National Geographic* prints dazzling pictures of natural landscapes, most of the time it does not bother saying what all those rocks are or what they mean.

This book is an attempt to present a global picture of modern science within the framework of the origin and evolution of the world in which we live. It provides the background necessary to understand why our planet is at risk. It also provides the background necessary for devising ways to stabilize the planet. The

treatment is quantitative and rigorous throughout, but no expertise other than a knowledge of English and arithmetic is needed. The emphasis is on facts, figures, quantities, and interrelationships, without which no true understanding of how anything works can be achieved. The book is divided into eight parts:

I. Prolegomena: science and religion
II. Matter and Energy
III. Cosmology
IV. Geology
V. Evolution of Life and Evnvironment
VI. The Historical Perspective
VII. Appendixes
VIII. References and Subject Index

Part I includes a discourse on how religion views the cosmos, a brief discussion of the twelve most imortant scientific discoveries that have brought about our modern understanding of the physical world, and a presentation of the units of measurement, which form the basic vocabulary of science.

Part II discusses in some detail the structure of matter, without which radioactivity, radiometric dating methods, and the geological time scale cannot be understood. States of matter and photons are included, and so is the Uncertainty Principle, one of the cornerstones of our world. Part II provides the reader with the background that is essential to understanding the rest of the material presented in the book.

Part III deals with cosmology, without which it is impossible to understand how Planet Earth became the way it is and works the way it does. This part begins with the birth of the universe and traces its subsequent evolution. The basic trigonometric fuctions, which are essential for describing celestial motions and many other things, are reviewed, and the various methods used to measure astronomical distances are discussed in some detail. An analysis of the different types of objects in the sky and their evolutionary histories are presented, followed by a discussion of the origin, evolution, geochemical differentiation, and present status of the solar system and its components. A discussion of the motions of the Earth in space and of the calendar and seasons concludes Part III.

At this point the reader is prepared to tackle that highly complex geophysical, geochemical, and biochemical system that we call Earth, the subject matter of Parts IV and V. Starting with the planet's geochemical composition, crystallography and mineralogy, petrology, geophysics, plate tectonics, atmosphere and ocean, weathering and soils, and terminating with sedimentation, fossil fuels, diagenesis and metamorphism, rock deformation, and stratigraphy, Part IV is, in fact a brief treatise on physical geology.

Parts V deals with the evolution of life and environment. Following an indispensable introduction to biochemistry and molecular biology, Part V discusses in some detail the origin of life on Earth and the subsequent biological and environmental evolution. The various taxa are introduced in the order in which they appeared in the fossil record. This will give the reader a direct appreciation for the immensity of time and the workings of evolution, which in 4.5 billion years produced *Homo sapiens* from scratch.

Part VI is a fairly extensive list of the men and women who contributed to scientific progress through the ages, with brief discussions of their major contributions. An alphabetical list of names is included.

Part VII includes a set of tables of physical chemical data, arranged in alphabetical order, and a Chemical Formulary. Part VIII gives a complete list of cited books and papers and a detailed subject index.

This is a multipurpose book in the sense that it can benefit a wide variety of people in different walks of life:

1. The casual lay reader will learn quite a bit about our planet, even if the math is ignored.

2. People in public life, in the legal system, or in business, who may be called on to take action or pass judgment on issues that will affect the environmental stability of the globe, will learn much of what they need to know to make wise decisions and take appropriate actions.

3. College students interested in learning how our world works should dig into this book with some aggressiveness. In fact, the subject matter in this book could provide the basis for a pair of highly relevant, college-

level science courses (first course, Part I–IV; second course, Part V) that would benefit both science and nonscience majors.

4. Science teachers in high schools, colleges, and universities will find that this book can lead to a better understanding of how the various areas of science integrate into a harmonious ensemble that explains how our world originated, evolved, and works; this understanding will make it easier for teachers to demonstrate to students at all levels the relevance of science to their lives.

The wealth of physical and chemical data and the Chemical Formulary in the appendixes are for reference and to help solve the Think questions that dot the book.

One who reads this book with any kind of attention will come to the inescapable conclusion that Planet Earth and the life on it form a truly remarkable system—a system that began with the Big Bang and culminated with the evolution of humans and their diversification into a rich variety of races, languages, and cultures. It is unfortunate that this diversification has led to chronic physical and cultural tribalism that, fanned by political and religious shamans of all shapes and colors, still rules the world. The failure of political and religious systems to evolve as rapidly as science has is now placing the entire planet at risk.

To deal with the serious problems that the world is now facing, we should follow the advice of Confucius—to expand knowledge as much as possible. From an informed citizenry new ideas can emerge that may provide the solutions that are desperately needed. There is no time to waste: All indications are that the next few decades will be quite difficult for us (see Chapter 24). If the political and religious philosophies that have made the twentieth century the bloodiest in the long and troubled history of humankind should carry over into the next, then the twenty-first century will be much, much worse. If, on the other hand, humans can succeed in burying the tribalism of the twentieth century and helping each other through the harsh times ahead, a new world should be waiting: better informed and better organized, with new machines doing much of the routine work, with enough food, shelter, health care, education, and leisure for everybody. Whether we get there or not will be determined by the children who are being born today. They will reach adulthood just as the Earth's economic and environmental crises force a decision: Change or perish. They will have to bury ancient philosophies, doctrines, and symbols; they will have to join hands with their brothers and sisters across continents and oceans; and they will have to come up with new ideas and new practices. To them, this book is dedicated.

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Cesare Emiliani
Coral Gables, Florida, April 1992

Greek alphabet

	Greek			Greek	
Latin	lowercase	uppercase	Latin	lowercase	uppercase
a	α	Α	o	ο	Ο
b	β	Β	p	π	Π
c	γ	Γ	r, rh	ρ	Ρ
d	δ	Δ	s	σ, ς	Σ
e	ε, ϵ	Ε	t	τ	Τ
z	ζ	Ζ	y	υ	Υ
e	η	Η	f	φ, ϕ	Φ
th	ϑ, θ	Θ	ch	χ	Χ
i	ι	Ι	ps	ψ	Ψ
k	ϰ, κ	Κ	o	ω	Ω
l	λ	Λ	ng	γγ	ΓΓ
m	μ	Μ	nk	γϰ	ΓΚ
n	ν	Ν	nx	γξ	ΓΞ
x	ξ	Ξ	nch	γχ	ΓΧ