Physics of Earth and Space Environments

Jürg Beer
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Cosmogenic Radionuclides

Theory and Applications in the Terrestrial and Space Environments

Springer

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With 196 Figures and 9 Tables

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It has taken eight years to write this book. When we started there was little interaction between the cosmogenic and cosmic ray research communities. As the book was written, that situation was changing rapidly. Many of our colleagues provided key insights, ideas and publications that hastened that change. In particular, the motivation towards close interaction came from both the cosmogenic and cosmic ray communities. Each community could see that the whole would be much greater than the sum of the two parts. We acknowledge this widespread contribution to the present day study and utilization of the cosmogenic radionuclides.

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Contents

List of Boxes

Abbreviations

ACR	Anomalous cosmic radiation
asl	Above sea level
AU	Astronomical unit
AMS	Accelerator mass spectrometry
B/M	Brunhes/Matuyama
CERN	The European Organization for Nuclear Research
CME	Coronal mass ejection
CMP	Central meridian passage
DNA	Deoxyribonucleic acid
DYE 3	Ice core drill site in South-Greenland
DOME C	Ice core drill site within EPICA
ECHAM	European Centre/Hamburg model
EPICA	European project for ice coring in Antarctica
FLUKA	Nuclear interaction software
GCM	General circulation model
GCR	Galactic cosmic rays
GEANT	Nuclear interaction software
GISP	Greenland ice sheet project
GLE	Ground level event
GMIR	Global merged interaction regions
GRIP	Greenland ice core project
HMF	Heliomagnetic field
HTO	"Tritiated water", ^3H_2O
IGY	International geophysical year
IMP	Interplanetary monitoring platform
INTCAL04	Radiocarbon age calibration data 2004
IPCC	Intergovernmental panel on climate change
IQSY	International quiet sun year
LIS	Local interstellar spectrum
MCNP	Monte Carlo N-Particle transport code

NASA	National aeronautics and space administration
NGRIP	North GRIP
PCA	Polar cap absorption or principal component analysis
SEP	Solar energetic particle (event)
SCR	Solar cosmic rays
SFU	Solar flux unit
SN	Supernova
SPE	Solar proton event (archaic)
SPECMAP	Mapping spectral variability in global climate project
STE	Stratosphere–troposphere exchange
THC	Thermohaline circulation
TSI	Total solar irradiance
UV	Ultraviolet
VADM	Virtual axial dipole moment
YD	Younger Dryas

Part I
Introduction

Chapter 1
Motivation

For a small child, the world is full of wonders. Everyday it discovers new ones. Soon it starts to ask tough questions like: "Why does an apple fall down from a tree, why does the water in an alpine river with large rocks partly flow uphill, why is the Sun hot and why does it turn red in the evening, how is a rock formed and when did it happen"?

These and many other questions have been asked since ancient times and the more people thought about them and made experiments, the more they learned about our environment and the way nature works. Many basic laws of nature have been discovered during the past centuries. These laws seem to be universally valid for all times. They are quite different from the laws made by humans which are influenced by the cultural and historical background of people and are subject to frequent changes. Nature's laws are the same in Europe, in Australia and on Mars. These laws help us understand what goes on, for example, deep in the Sun. By analyzing all the information available from the Sun in the form of light, particles (solar wind, neutrinos), magnetic fields, and the dynamics (sunspots, helioseismology) solar physicists are able to develop models of the interior of the Sun and how energy is generated there and transported out into the solar system. However, in spite of the impressive progress in natural sciences, with every answered question at least one new one arises and we are still far from understanding how nature really works.

We humans are living on the surface of planet Earth, two-third of which is covered by water, the essence of life. This water makes Earth look blue from space except for the continents and the white clouds which cover a considerable part as well. A very thin layer of gas, the atmosphere, separates us from space and protects us from harmful particles (cosmic rays) and radiation (UV, X-rays). All the men on the moon were deeply impressed when they saw the Earth for the first time from far away (Fig. 1-1).

The Earth is a very dynamic and complex system powered by solar energy. Life, which has existed for almost as long as the solar system, has modified the environment on Earth. Vegetation affects the hydrological cycle and changes the albedo,

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Fig. 1-1 Earthrise seen from the moon. Apollo 8 crew Christmas 1968 (*NASA*)

Fig. 1-2 Earth seen from the Cassini spacecraft from behind Saturn (Cassini Imaging Team, SSI, JPL, ESA, NASA)

the portion of solar radiation which is reflected back into space. Photosynthesis alters the composition of the atmosphere, which was originally free of oxygen, by turning CO_2 into O_2. In recent times, the growth of the Earth's population and the increasing consumption of energy per capita marks the beginning of a new era. By burning huge amounts of fossil fuels, we humans are increasing the atmospheric

CO_2 concentration to levels far above the values attained during at least the past million years. In other words, mankind has started a big experiment by considerably modifying the natural global conditions. Now, understanding how nature works and studying the consequences of our activities will be no longer simply an intellectual game for unworldly scientists. It is becoming a serious challenge with potentially large impacts on all of us living on the tiny spot called Earth photographed by the Cassini spacecraft from behind Saturn (Fig. 1-2).

To successfully address the question of global change in the past, present and future, we need to employ a holistic approach that crosses the boundaries between many disciplines. This book talks about cosmogenic radionuclides, radioactive isotopes which are produced and distributed within the earth system. It shows how they can be used to trace and to reconstruct the history of a large variety of processes. The authors hope to convey to the reader the beauty and the potential these tools have to contribute to the solution of many present and future problems.

Chapter 2
Goals

Richard Feynman (Feynman et al. 1963) began his famous "Lectures on Physics" with the question: "*If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words?*" His answer was: "*I believe it is the atomic hypothesis that all things are made up of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*"

We know today that everything in the universe, the stars, the planets and ourselves are made up of only about 90 different atoms (the elements) which themselves consist of just three particles: protons, neutrons, and electrons. A 100 years ago, only physicists and chemists studied and made use of atoms, and this was regarded then as "fundamental science". The word physics, however, is derived from the Greek word physis (ΦΥΣΙΣ) and means "nature", or the science of matter in space and time. All the natural sciences (and applications thereof) ultimately deal with the interaction and the motion of atoms and frequently the best (and sometimes the only) way to study these interactions is to trace the individual atoms themselves.

Today there is hardly a scientific profession that does not use atomic or nuclear techniques on a day to day basis – in lasers, in specialized semiconductors, in studying the growth of plants, in magnetic resonance tomography, and so on. This book deals with yet another application: the ability to use isotopes, and in particular the radioisotopes, to permit the study of a great number of environmental processes.

Until recently, the precise measurement of small quantities of atoms was an extremely difficult task, and this impeded the development of the applications that have blossomed over the past two decades. Stable isotopes are traditionally measured by mass spectrometers and both mass resolution and precision have steadily improved, together with a reduction in sample size. Radioisotopes had been measured by radioactive decay counting; however, this is very inefficient for radionuclides with long half-lives. The invention of the accelerator mass spectrometry technique (AMS) in the late 1970s revolutionized the field, enabling the measurement of isotopic ratios as low as 10^{-14} and increasing sensitivity by

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5–6 orders of magnitude. The importance of such an increase may be illustrated by an analogy from astronomy. Imagine a Greek astronomer who was observing the stars with the 5 mm wide iris of his naked eye. Switching to AMS was equivalent to giving our ancient astronomer access to the 5 m telescope at Mount Palomar.

The cosmogenic radionuclides have been generated here on Earth, in quite miniscule amounts, from time immemorial. They were created by the cosmic radiation that bombards the Earth, and they provide a record of astronomical, solar, and Earth bound events that extend far into the past. Until recently, we did not have the means to read or decipher these records. However, as a result of the analytical advances outlined above, the number of applications of cosmogenic radionuclides to understand the past and investigate the present is growing rapidly and spreading over many scientific disciplines. The number of students and scientists working with cosmogenic radionuclides is steadily increasing, and with it the need for a comprehensive overview of what cosmogenic radionuclides are, and a discussion of their potential and their (present-day) limitations.

To date, some specialised review articles, conference proceedings, and a few books have appeared dealing with cosmogenic radionuclides as tracers and as dating tools, the primary focus being on specific fields of applications with only passing discussions of the basic underlying concepts and mechanisms. The main goal of this book is to provide the reader with a comprehensive discussion of the basic principles lying behind the applications of the cosmogenic (and other) radionuclides.

Part I (Chaps. 1–3) provides an introduction to the book and outlines the goals.

Part II (Chaps. 4–8) provides the background knowledge of the properties of the cosmic radiation that will allow the reader to understand the concepts, terminology, and formulae that are used later in the book.

Part III (Chaps. 9–15) of the book is dedicated to the cosmogenic radionuclides and discusses in some detail their production by the cosmic radiation, their transport and distribution in the atmosphere and the hydrosphere, their storage in natural archives, and how they are measured. A good understanding of these basics is a prerequisite for optimal use of cosmogenic radionuclides as environmental tracers and dating tools.

Part IV (Chaps. 16–23) deals with applications of cosmogenic radionuclides. It presents a number of examples selected to illustrate typical tracer and dating applications in a number of different spheres (atmosphere, hydrosphere, geosphere, biosphere, solar physics and astronomy). The goal of this part is not to give a comprehensive overview of all the many different applications developed so far. Its aim is to give the reader an understanding of what is possible, and possibly to provide the insight and motivation to develop new applications. At the same time, we have outlined the limitations of the use of cosmogenic radionuclides, to prevent unfortunate experiences in the future.

We are aware that we are addressing a wide audience, ranging from archaeology, biophysics, and geophysics, to atmospheric physics, hydrology, astrophysics and space science. We have therefore tried to explain everything at the level of a graduate student without specialist skills in physics or mathematics. To provide the reader with more technical details, or the derivation of a few interesting equations, we use boxes which are separated from the main text and are not mandatory in order to understand the basic ideas. We would rather bore the specialists in their own field with "trivial" matter, than to keep others from understanding important concepts they are not familiar with. For the same reason, and to make reading individual chapters easier, we provide extensive internal referencing, and occasionally some basic information is repeated briefly in the introductions to chapters on specific applications.

Finally we express our hope that this book will help the reader to achieve a greater understanding of the use of the cosmogenic radionuclides, and also to enjoy the thrill of using this marvellous technology to uncover the mysteries of the past, and the world around us as we authors do.

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Chapter 3
Setting the Stage and Outline

In this chapter we set the stage for the rest of the book by introducing the terrestrial and space environments and the cosmogenic radionuclides. The main purpose of this general overview is to show that the terrestrial and space environments are large complex coupled systems and that cosmogenic radionuclides are extremely useful tools to better understand how these systems work and interact, and to reconstruct their history and even to some extent predict their future.

We stress the fact that the environment is a single, internally coupled system. By convention, and for simplicity, we usually divide it into subsystems; however, the interaction of these subsystems must always be kept in mind. A further complication is that there are no sharp boundaries between the sub-systems themselves. Thus the boundaries between the geosphere and the hydrosphere are indistinct, as are those between the atmosphere and space. It is impossible to pinpoint the top of the Earth's atmosphere because the density of the atmosphere decreases exponentially and merges into the space environment over a considerable distance. Here on Earth, the properties of artesian water depend on the geological setting. It is important to bear in mind that the terrestrial and space environments, and the various sub-systems, are open systems which means that there is continuous exchange of energy and matter between them.

The cosmogenic radionuclides are an important consequence of processes occurring in the galaxy, the Sun, and in the atmosphere. They are generated by the cosmic radiation (protons, He, and heavier nuclei and electrons) that were accelerated to very high energies in supernova explosions within our galaxy and which have then travelled at almost the speed of light to the vicinity of our Sun, entering a region called the heliosphere. Their intensity is modified as they pass through the heliosphere, and then on entering the atmosphere they have collided with the nucleus of an atom and have broken it up into the smaller, unstable cosmogenic radionuclides (radioactive nuclides produced by cosmic rays).

In Fig. 3-1 we summarize the essence of this book in one single diagram. It is a sketch of the terrestrial and space environments consisting of the many components such as the land, ocean, lakes, rivers, vegetation, clouds, volcanoes, the Sun, cosmic rays, and so on. Traditionally the environment is divided into systems or spheres,

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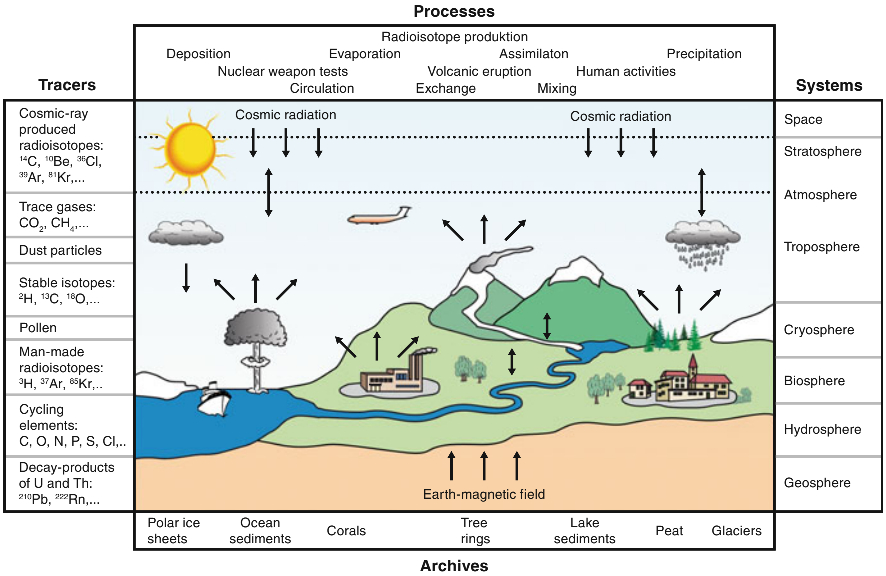

Fig. 3-1 The terrestrial and space environment divided into the subsystems listed on the *right-hand side*. Basic processes are listed in the *top panel*. They can be studied using tracers mentioned on the *left-hand side*. Information about the past environmental changes is stored in natural archives (*bottom panel*)

and these are indicated on the right-hand side of the figure. The environment is a dynamic system driven in large part by solar energy, in which many different processes are involved in the transport and distribution of energy and matter. Some of these processes are listed on the top of Fig. 3-1.

The basic goal of environmental science is to understand this large variety of physical, chemical, geological, and biological processes, their couplings and their spatial and temporal variability, and ultimately to construct an Earth system model which includes all the relevant processes. To achieve this goal we need to investigate the different processes themselves, and their interplay. However, it is often very difficult to study environmental processes because of their three-dimensional nature, their scale, and their inhomogeneity. A good example is the flow of underground water which is invisible and potentially very complex. We have long used "tracers" to this end; dyes and other chemicals that allow us to follow the motion of the water underground. The cosmogenic radionuclides play an important role here, as summarized in the list on the left-hand side of Fig. 3-1.

In general, tracers are tiny amounts of substances which are either naturally or artificially added to a system such as a water flow that allow us to document its movement over space and time. In the example of a groundwater system, the traditional approach was to use dyes and coloured material – we speak of such as having the property of "colour". A tracer must fulfil several conditions: (1) it must be discernible from the medium it is added to, (2) it should be conservative – i.e. it must behave in a predictable manner and not influence the system into which it is introduced, and (3) it must be easily detectable. As artificial tracers may cause disturbance of a natural system or social resistance (even if the amount is negligibly small) it is preferable to use natural tracers whenever it is possible.

The list of tracers in Fig. 3-1 shows that a considerable number of them are the naturally occurring cosmogenic radionuclides. The fact that they decay after a precisely known mean lifetime offers the additional opportunity to not only trace the pathway, but also to determine timing. In other words, while most tracers just carry “colour”, radionuclides carry a “colour” and a “clock” at the same time. Furthermore, due to their continuous production and radioactive decay, their source and sink functions are rather well known. The large range of different geochemical properties and half-lives of the cosmogenic radionuclides allows the user to select the one which is the most appropriate for the problem in hand.

The beauty of many tracers is that not only are they very useful tools in the study of processes going on at present, but they can also provide unique information about the past. This is particularly important because most of the important processes in the environmental system (such as climate change) occur on decadal to millennial or even geological time scales. While the amount of information provided by earth and space bound instruments has been almost unlimited for the past several decades, we face an increasing lack of environmental information the further we go back in time. Fortunately mother Earth has been keeping track of past environmental conditions in her own diaries, the natural archives. Many processes and parameters are recorded in ice cores, sediments, tree rings, and the other archives listed in the row at the bottom of Fig. 3-1. The cosmogenic radionuclides play a fundamental role here in establishing the time scales and in dating important past events. The information in the archives provides us a better understanding of the past, which is the key to predicting the future.

Having set the stage we now take the reader on a tour through the book. It is divided into four parts, starting with this introductory part. Part II provides an overview of the cosmic radiation. Chapter 5 starts with some historical remarks and definitions, and then outlines the origin and the properties of the galactic cosmic rays. The Sun’s effects on the propagation of cosmic rays through the heliosphere are summarized and then finally the effects of the geomagnetic field are outlined. Chapter 6 is dedicated to the instruments that have been used to measure the cosmic radiation. Chapter 7 discusses the various effects that lead to temporal variations of the cosmic radiation that, in turn, lead to temporal variations in the cosmogenic archives. Chapter 8 deals with the cosmic radiation produced by the Sun and its specific properties.

In Chap. 9, we go to Part III and introduce the cosmogenic radionuclides which are the product of the interaction of the cosmic radiation with matter. In Chap. 10, we address the interactions of cosmic rays with the atmosphere and how a cascade of secondary particles develops which finally leads to the production of the individual cosmogenic radionuclides. This chapter outlines how Monte Carlo techniques are used to compute the neutron and proton fluxes throughout the atmosphere (including the solar and geomagnetic effects) and then compute the cosmogenic production rates. Chapter 11 discusses cosmogenic production in environmental systems other than the atmosphere, while in Chap. 12 other production mechanisms are addressed.

Chapter 13 deals with the vital matter of the manner in which atmospheric processes distribute and deposit the cosmogenic radionuclides on the Earth's surface. The geochemical cycles are different for the various cosmogenic radionuclides, as addressed in this chapter.

Some of the cosmogenic radionuclides are then incorporated into natural archives where their unique record of the past is stored over long periods of time. The most common natural archives and their main properties are described in Chap. 14. The last chapter of this part of the book deals with the techniques used to measure the cosmogenic radionuclides in natural archives.

The last part of the book is dedicated to applications. It presents a selection of typical examples that demonstrate the power of cosmogenic radionuclides to investigate various processes within the environmental system. The examples are from Solar Physics and Astronomy in Chaps. 17 and 18 and from the other systems, shown in Fig. 3-1: the atmosphere (19), the hydrosphere (20), the geosphere (21), and the biosphere (22). The last chapter of this book finally discusses the applications related to dating past events.

Part II
Cosmic Radiation

Chapter 4
Introduction to Cosmic Radiation

Long before the first animals emerged from the oceans to live on land, before the rise and fall of the dinosaurs, and long before the Neaderthals roamed the Earth, supernovae throughout our galaxy were happily making cosmic rays that then bombarded Earth. Long before mankind developed the ability to keep records, the cosmic rays were leaving behind indelible records that now, millions of years later, we have learned to read. Those records were written in an ink that consisted of the "cosmogenic radionuclides" produced by the cosmic rays when they smashed asunder atoms in our atmosphere. Those cosmogenic records tell us about the past behaviour of our Earth, our Sun, and our galaxy. They provide us with the means to study our atmosphere, water resources, to date archaeological discoveries, and do many other things that enrich our lives.

The cosmic radiation has complex characteristics, and varies from day to day, year to year, century to century and over timescales of many thousands of years. These characteristics, and time variations, both help and hinder our interpretation of the cosmogenic records. They allow us to use cosmogenic data to investigate the manner in which the Sun has varied over the past millennia that will assist us to understand climate change, and to avoid expensive damage to our satellite communication systems. At the same time, they complicate the carbon dating of archaeological materials. To exploit the good things, and minimise the bad, it is necessary to understand (or at least, look up) the properties of the cosmic rays without which we would have no cosmogenic records, or practical applications.

It is only in the past two decades or so that we have had the means to determine, in a quantitative manner, the relationship between the cosmic radiation and the production of the cosmogenic radionuclides. Two major technological advances made that possible. (1) Instrumentation on earth orbiting satellites and deep space probes provided a detailed knowledge of the composition, energy dependence, and time dependence of the cosmic radiation. (2) Large numerically intensive computers and highly complex mathematical codes that simulate the propagation of the cosmic rays in the atmosphere provided the ability to use satellite data to interpret the cosmogenic data from the past. The development of the Accelerator

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