Atmospheric Evolution on Inhabited and Lifeless Worlds

As the search for Earth-like exoplanets gathers pace, in order to understand them, we need comprehensive theories for how planetary atmospheres form and evolve. Written by two well-known planetary scientists, this text explains the physical and chemical principles of atmospheric evolution and planetary atmospheres, in the context of how atmospheric composition and climate determine a planet's habitability. The authors survey our current understanding of the atmospheric evolution and climate on Earth, on other rocky planets within our Solar System, and on planets far beyond. Incorporating a rigorous mathematical treatment, they cover the concepts and equations governing a range of topics, including atmospheric chemistry, thermodynamics, radiative transfer, and atmospheric dynamics, and provide an integrated view of planetary atmospheres and their evolution. This interdisciplinary text is an invaluable onestop resource for graduate-level students and researchers working across the fields of atmospheric science, geochemistry, planetary science, astrobiology, and astronomy.

David C. Catling is a Professor in Earth and Space Sciences at the University of Washington, Seattle, who studies planetary surfaces, atmospheres, and habitability. He actively participates in the research of NASA's Astrobiology Institute and is the author of *Astrobiology: A Very Short Introduction* (2013). He has taught courses in planetary atmospheres, planetary geology, astrobiology, and global environmental change at undergraduate and graduate levels. He was also an investigator for NASA's Phoenix Mars Lander, which successfully operated in the arctic of Mars during 2008.

James F. Kasting is an Evan Pugh Professor of Geosciences at The Pennsylvania State University, and an acknowledged expert on atmospheric and climate evolution. He is the author of the popular book, *How to Find a Habitable Planet* (2010) and coauthor of the introductory textbook, *The Earth System* (3rd edn, 2009). Dr. Kasting has received numerous awards, including that of Fellow of the American Geophysical Union, the Geochemical Society, the International Society for the Study of the Origin of Life (ISSOL), the American Academy for the Advancement of Science, and the American Academy of Sciences. He received the Oparin Medal from ISSOL in 2008, and the Stanley Miller Medal from the National Academy of Sciences in 2016.

Atmospheric Evolution on Inhabited and Lifeless Worlds

David C. Catling
University of Washington

James F. Kasting
Pennsylvania State University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521844123

First published 2017

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication data
Names: Catling, David (David Charles) | Kasting, James F.
Title: Atmospheric evolution on inhabited and lifeless worlds / David C. Catling,
University of Washington, James F. Kasting, Pennsylvania State University.
Description: Cambridge : Cambridge University Press, 2017. | Includes bibliographical
references and index.
Identifiers: LCCN 2016030819 | ISBN 9780521844123 (hardback : alk. paper)
Subjects: LCSH: Atmosphere. | Atmosphere, Upper. | Planets–Atmospheres. |
Geochemistry.
Classification: LCC QC861.3 .C38 2017 | DDC 551.5–dc23 LC record available at
https://lccn.loc.gov/2016030819

ISBN 978-0-521-84412-3 Hardback

Contents

Preface

For millennia, philosophers have offered mere opinions about whether life exists beyond the Earth, but amazingly it will soon be possible to replace such conjectures with data. In other words, we stand on the brink of solving the question of "are we alone?" The answer may come from the spectrum of an exoplanet, from rocks on Mars, or from some unexpected source. In any case, we now know that our galaxy contains billions of exoplanets, some of which may be inhabited. This problem focuses our attention on what makes a planet habitable. When we look at Earth, Mars and Venus, we see that an atmosphere – through composition and climate – plays a critical role in distinguishing lifeless from inhabited planets. Thus, the topic of *atmospheric evolution* is essential. We need to know where atmospheres come from, how atmospheres remain stable, how the mixture of gases in an atmosphere changes over billions of years from the origin of a planet to its current or future state, and whether an atmosphere can provide a climate conducive to life.

We have been working on various aspects of atmospheric evolution for two (DCC) and four decades (JFK), respectively. Both of us have been fortunate in receiving continual support from NASA's Exobiology Program and the NASA Astrobiology Institute. We have previously published reviews on relevant topics, such as the physics and chemistry of atmospheres (Catling, 2015) (which we expand in Chapters 1–5), the origin and habitability of the Earth (Kasting and Catling, 2003) (which we bring up-to-date in Chapters 6–11), oxygenation of Earth's atmosphere (Catling, 2014; Kasting, 2013) (which is newly reviewed in Chapter 10), astrobiology (Catling, 2013) (a theme throughout this book), and searching for habitable planets (Kasting, 2010) (which is the topic of Chapter 15). Our reviews have been at different levels, and, for the researcher, useful information has remained very scattered across the scientific literature. Such dispersal arises because aspects of astronomy, geology, geochemistry, and atmospheric science all contribute to the formation and evolution of atmospheres. On a planet with life, we must add biology also. Consequently, we wrote this book to gather our knowledge of planetary atmospheres into a framework of atmospheric evolution and habitability. Our intended reader is any interested researcher or graduate student.

In this book, we are concerned with inhabited planets such as Earth, as well as lifeless ones. But the Earth itself changed from being lifeless to inhabited. We also consider other inhabited planets in the context of possible life on early Mars or potential life on exoplanets that might be remotely detectable. As mentioned above, whether a planet is inhabited or lifeless is a key motivation to study atmospheric evolution. All of these considerations led us to the title of this book.

The book has three parts. In Part I, we concisely describe principles of atmospheres (structure, radiation, chemistry, and motions) that are needed to appreciate atmospheric evolution and habitability. Part II describes origins of atmospheres and the evolution of Earth's atmosphere and climate. Finally, Part III turns to other worlds, including Mars, Venus, outer planet satellites, and exoplanets.

Because atmospheric evolution ranges over a vast swath of disciplines that stretches the limits of our expertise, colleagues have kindly provided essential help. In alphabetical order, we thank the following people for commenting on individual chapters: Dorian Abbot, Don Brownlee, John Chambers, Nick Cowan, Colin Goldblatt, David Grinspoon, Paul Hoffman, Dick Holland, Edwin Kite, Conway Leovy, Ralph Lorenz, Vikki Meadows, Tyler Robinson, Adam Showman, Jon Toner, and Steve Warren. We also thank Beth Tully for her patience in helping us with the diagrams. We owe special thanks to a couple of departed friends on our list who are greatly

missed. These colleagues always generously shared their ideas and unfailingly provided eager encouragement. They were Conway Leovy (1933–2011) and Heinrich ("Dick") Holland (1927–2012). We would also like to acknowledge James C.G. Walker, who was a mentor to JFK, and who in 1977 wrote a previous book titled *Evolution of the Atmosphere* that has guided thinking on this topic for about the past 40 years. Finally, we thank Vince Higgs at CUP for enormous patience in waiting for us to complete this book.