

## 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.

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## 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

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