# Cosmochemistry

Cosmochemistry is a rapidly evolving field of planetary science and the second edition of this classic text reflects the exciting discoveries made over the past decade from new spacecraft missions. Topics covered include the synthesis of elements in stars, behavior of elements and isotopes in the early solar nebula and planetary bodies, and compositions of extra-terrestrial materials. Radioisotope chronology of the early Solar System is also discussed, as well as geochemical exploration of planets by spacecraft, and cosmochemical constraints on the formation of solar systems. Thoroughly updated throughout, this new edition features significantly expanded coverage of chemical fractionation and isotopic analyses; focus boxes covering basic definitions and essential background material on mineralogy, organic chemistry and quantitative topics; and a comprehensive glossary. An appendix of analytical techniques and end-of-chapter review questions, with solutions available at www.cambridge.org/cosmochemistry2e, also contribute to making this the ideal teaching resource for courses on the Solar System's composition as well as a valuable reference for early career researchers.

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For Sue and Jackie

# Contents

# Preface

Cosmochemistry provides critical insights into the workings of our local star and its stellar companions throughout the galaxy, the origin and timing of our solar system's birth, and the complex processes inside planetesimals and planets (including our own) as they evolve. Much of the database of cosmochemistry comes from laboratory analyses of elements, compounds, and isotopes in our modest collections of extraterrestrial samples. A growing part of the cosmochemistry database is gleaned from remote-sensing measurements by spacecraft instruments, which provide chemical analyses and geologic context for other planets, moons, asteroids, and comets. Because the samples analyzed by cosmochemists are typically so small and valuable, or must be analyzed on bodies many millions of miles distant, this discipline leads in the development of new analytical technologies for use in the laboratory or on spacecraft. These technologies then spread to geochemistry, materials science, and other fields where precise analyses of tiny samples are important.

Despite its cutting-edge qualities and often newsworthy discoveries, cosmochemistry is an orphan. It does not fall clearly within the purview of chemistry, physics, geology, astronomy, or biochemistry but is rather an amalgam of parts of these disciplines. Because it has no natural home or constituency, cosmochemistry is usually taught (if it is taught at all) directly from its scientific literature (admittedly challenging reading) or from specialized books on meteorites and planetary science. In crafting the original edition of this textbook, we attempted to remedy that shortcoming. In this thoroughly revised second edition, we have incorporated new discoveries made and novel insights gleaned during the last decade. We have tried to make this subject accessible to advanced undergraduate and graduate students with diverse academic backgrounds, although we do presume some prior exposure to basic chemistry. This goal may sometimes lead to uneven treatment of some subjects, and our readers should understand that our intended audience is broad.

Cosmochemistry is advancing so rapidly that we can only hope to provide a snapshot of the discipline as it is currently understood and practiced. We have found even that to be a challenge because we could not hope to possess expertise in all the subjects encompassed by this discipline. We have drawn heavily on the contributions of many colleagues, especially those who educate by writing thoughtful reviews. That assistance is gratefully acknowledged through our annotated suggestions for further reading at the end of each chapter.

The topics covered in the chapters of this book include the following, in this order:

- Introduction to how cosmochemistry developed, and to how it differs from geochemistry
- Basic review of the characteristics and behaviors of elements and isotopes
- Discussion of how elements are synthesized within stars, and how the chemistry of the galaxy has evolved over time
- Assessment of the abundances of elements and isotopes in the solar system, and how they are measured
- Description of presolar grains found in meteorites, and how they constrain nucleosynthesis in stars and processes in interstellar space
- Introduction to meteorites, interplanetary dust particles, and lunar samples
- Consideration of processes that have fractionated elements in interstellar space, in the solar nebula, and within planetary bodies
- Consideration of processes that fractionate stable isotopes, as well as isotopic anomalies inherited from the Sun's parent molecular cloud
- Explanation of how long-lived and short-lived radioactive isotopes are used to quantify solar system history
- Synthesis of the radiometric age of the solar system and the ages of its constituents
- Assessment of the solar system's most volatile materials: ices, noble gases, and organic matter
- Survey of planetesimals to provide context on planetary building blocks
- Assessment of the chemistry of asteroids and comets, based on the samples we have of them and on spacecraft remote sensing

- Examples of modern geochemical exploration of solar system bodies: the Moon and Mars
- Synthesis and review of the formation of solar systems, from the perspective of cosmochemistry
- Appendix describing some important analytical methods used in cosmochemistry

More established disciplines are taught using tried-and-true methods and examples, the results of generations of pedagogical experimentation. Cosmochemistry does not yet offer that. Most of those who dare to teach cosmochemistry, including the authors of this book, have never actually been students in a cosmochemistry course. In the authors' case, we have learned directly from a handful of scientists who have guided our introduction to the field, including Calvin Alexander, Bob Pepin, Ed Anders, Jim Hays, Dick Holland, Ian Hutcheon, Klaus Keil, Roy Lewis, Dimitri Papanastassiou, Jerry Wasserburg, and John Wood, and indirectly from many professional colleagues and our own students. We hope that this introduction to cosmochemistry will guide other students and their teachers as they explore together this exciting, interdisciplinary subject, and that they will enjoy the experience as we have.