Cosmochemistry

How did the solar system's chemical composition arise and evolve?

This textbook provides the answers in the first interdisciplinary introduction to cosmochemistry. It makes this exciting and evolving field accessible to undergraduate and graduate students from a range of backgrounds, including geology, chemistry, astronomy, and physics.

The authors – two established research leaders who have helped pioneer developments in the field – provide a complete background to cosmochemical processes and discoveries, enabling students outside geochemistry to fully understand and explore the solar system's composition.

Topics covered include:

- synthesis of nuclides in stars
- partitioning of elements between solids, liquids and gas in the solar nebula
- overviews of the chemistry of extraterrestrial materials
- isotopic tools used to investigate processes such as planet accretion and element fractionation
- chronology of the early solar system
- geochemical exploration of planets.

Boxes provide basic definitions and mini-courses in mineralogy, organic chemistry, and other essential background information for students. Review questions and additional reading for each chapter encourage students to explore cosmochemistry further.

HARRY (Hap) Y. McSWEEN Jr. is Chancellor's Professor at the University of Tennessee. He has conducted research on cosmochemistry for more than three decades and was one of the original proponents of the hypothesis that some meteorites are from Mars. He has been a co-investigator for four NASA spacecraft missions and serves on numerous advisory committees for NASA and the US National Research Council. Dr. McSween has written or edited four books on meteorites and planetary science, and coauthored a textbook in geochemistry. He is a former president and Fellow of the Meteoritical Society, a Fellow of the American Academy of Arts and Sciences, recipient of the Leonard Medal, and has an asteroid named for him.

GARY HUSS is a Research Professor and Director of the W. M. Keck Cosmochemistry Laboratory at the Hawai‘i Institute for Geophysics and Planetology, University of Hawai‘i at Mānoa. In more than three decades of research on cosmochemistry, he was among the first to study presolar grains, the raw materials for the solar system. He presently studies the chronology of the early solar system. He comes from a family of meteorite scientists: his grandfather, H. H. Nininger, has been called the father of modern meteoritics, and his father, Glenn Huss, and grandfather were responsible for recovering over 500 meteorites previously unknown to science. Dr. Huss is a former president and Fellow of the Meteoritical Society and also has an asteroid named for him.

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Harry Y. McSween, Jr. and Gary R. Huss
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More information

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Harry Y. McSween, Jr.
University of Tennessee, Knoxville

Gary R. Huss
University of Hawai'i at Mānoa

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For Sue and Jackie

Contents

Preface

Cosmochemistry provides critical insights into the workings of our local star and its companions throughout the galaxy, the origin and timing of our solar system's birth, and the complex reactions inside planetesimals and planets (including our own) as they evolve. Much of the database of cosmochemistry comes from laboratory analyses of elements and isotopes in our modest collections of extraterrestrial samples. A growing part of the cosmochemistry database is gleaned from remote sensing and *in situ* measurements by spacecraft instruments, which provide chemical analyses and geologic context for other planets, their 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 flown on spacecraft missions. These technologies then spread to geochemistry and other fields where precise analyses of small samples are important.

Despite its cutting-edge qualities and newsworthy discoveries, cosmochemistry is an orphan. It does not fall within the purview of chemistry, geology, astronomy, physics, or biology, but is rather an amalgam 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 difficult reading) or from specialized books on meteorites and related topics. In crafting this textbook, we attempt to remedy that shortcoming. 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 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:

- An introduction to how cosmochemistry developed, and to how it differs from geochemistry
- A review of the characteristics and behaviors of elements and nuclides
- A discussion of how elements are synthesized within stars, and how the chemistry of the galaxy has evolved over time

- An assessment of the abundances of elements and isotopes in the solar system
- A description of presolar grains, and how they constrain stellar nucleosynthesis and processes in interstellar space
- An introduction to meteorites and lunar samples
- An evaluation of processes that have fractionated elements and isotopes in interstellar space, in the solar nebula, and within planetary bodies
- An explanation of how radioactive isotopes are used to quantify solar system history
- A synthesis of the radiometric age of the solar system and the ages of its constituents
- An assessment of the most volatile materials – organic matter, noble gases, and ices
- A survey of the chemistry of anhydrous planetesimals and the samples we have of them
- A survey of the chemistry of ice-bearing comets and asteroids and the samples we have of them
- Examples of modern geochemical exploration of planetary bodies – the Moon and Mars
- A review of the formation of the solar system, from the perspective of cosmochemistry
- An 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 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. We hope that this book on cosmochemistry will guide other students and their teachers as they explore together this emerging, interdisciplinary subject, and that they will enjoy the experience as much as we have.