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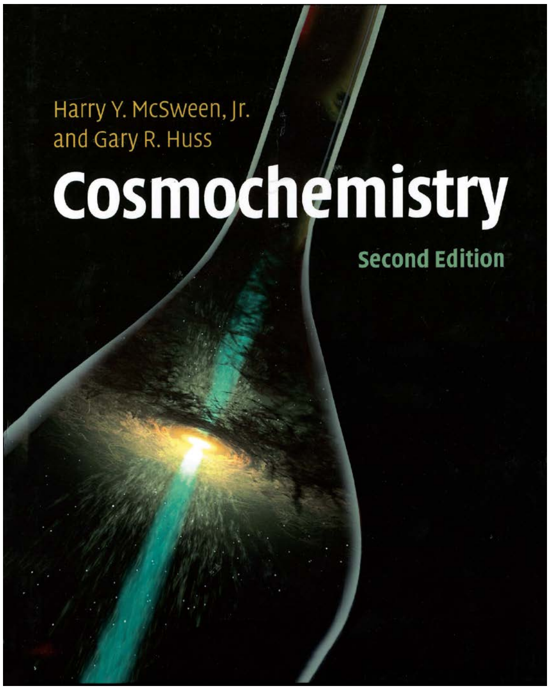
BOOK REVIEW

Book Review: **Cosmochemistry, 2nd edition** (2022) By Harry McSween Jr. and Gary Huss. Cambridge. ISBN: 9781108839839, 452 pages. $79.99.



Cosmochemistry (2022) is a revised and updated version of a textbook originally published in 2010. For those familiar with the original version, text in the new edition is in two columns, sections are numbered, and boxes describing topics in more detail are more clearly distinguished from the main text. These changes make for easier reading, review, and navigation. In most cases figures are clearer, less-useful figures have been removed, and the new edition includes 14 color plates, with a glossary. An Appendix describing the most commonly used analytical techniques is updated. Most importantly, the content has been updated to reflect significant discoveries in the field within the past decade.

The textbook is suitable for an upper-level undergraduate or graduate level course. The authors define *cosmochemistry* as the study of the chemical compositions of the universe and its constituents, drawing on aspects of chemistry, physics, geology, astronomy, astrophysics, and even biology. They make the distinction between geochemistry and cosmochemistry, noting that the behavior of the elements is different in the solar nebula—as reflected in chondrite meteorites—from the behavior within geologic processes on the Earth. The latter are nevertheless important for interpreting data from other planetary bodies (such as the Moon or Mars), and the term *planetary geochemistry* is defined and included as part of cosmochemistry. Whereas the majority of the information in cosmochemistry comes from the study of samples—primarily meteorites but also interplanetary dust particles (IDPs) and lunar rocks—the authors acknowledge and summarize the wealth of data that comes from the exploration of the solar system by spacecraft, whether that exploration includes sample return (as listed in Table 1.1 of the text) or not. Observations of Jupiter, Saturn, Uranus, and Neptune and their icy satellites, comets, and Pluto and other Kuiper Belt Objects (KBOs) are integrated throughout the book, particularly in a chapter on Ices, Noble Gases, and Organic Matter, as well as in the concluding chapter on Models for the Formation and Evolution of Solar Systems.

Each chapter of the book is detailed and well organized, and includes an introductory paragraph, a summary section, questions for comprehension, suggestions for further reading, and a bibliography. The chapters are obviously meant to be followed in sequence, with concepts in later chapters building on those in the earlier ones. The reader is introduced to the basics of nuclear physics, the nuclides and the origin of radioactivity, the periodic table and bonding, nucleosynthesis and the life cycles of stars, and the solar system abundances of the elements and isotopes in early chapters. Tables of abundance data make for good reference material. A fascinating summary of the origin of our galaxy and its chemical evolution in Chapter 3 provides a sort of pre-history for our solar system. The historical perspective is given for a range of topics; this approach works especially well for the chapter on presolar grains, which outlines the "detective story" involved in finding the carriers of unusual Xe isotopes, culminating in our current ability to infer the conditions around other stars based on the mineralogy and isotopic compositions of these grains, and constrain stellar evolution models. There is even a discussion of the potential for constraining the age of the galaxy (see Box 5.1 therein).

The main samples used in cosmochemistry are described in their own chapter, including the components in chondrite meteorites, the classification of meteorites, and descriptions of

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IDPs and lunar rocks from the Apollo and Luna missions. Photomicrographs in this chapter are a bit washed out, and would have made for good color plates. The classification scheme is generally comprehensive, lacking only the most recently described carbonaceous chondrite chemical groups (CL and CY). The criteria for shock stage are not provided, but a reference is included. The most up-to-date weathering classification scheme is lacking. If this textbook were used for a course that included a lab component, it would be best supplemented with other sources (such as Grady et al. 2014, *Atlas of Meteorites,* Cambridge).

This new edition of *Cosmochemistry* splits a chapter on cosmochemical and geochemical fractionations from the previous edition into two chapters, one on elemental fractionations and the other on stable-isotope fractionations. This works well; the former discusses the various ways in which elements are fractionated from one another in the nebular and planetary contexts, including during condensation or evaporation, partial melting and fractional crystallization, aqueous fluid activity, changes in oxidation state, as well in the sorting of chondrite components, impacts, and other physical processes. Further details relating to the cosmochemical behavior of elements as introduced in an earlier chapter are developed and calcium-aluminum inclusions (CAIs) are treated in this context, resulting in an in-depth review that is useful for any researcher in the field. The differentiation of planets and planetesimals, including of gas giants and icy bodies, is also discussed. The latter chapter provides fundamental background on stable isotope geochemistry, including both equilibrium and kinetic mass-dependent fractionations, with applications to geothermometry and aqueous alteration conditions in meteorites. The important recent development of clumped-isotope analysis is presented. Applications of these types of fractionations to cosmochemistry are well described, from the temperature of formation of carbonate minerals in the ALH 84001 martian meteorite, to the high δ^{15}N and D/H values of organic matter in carbonaceous chondrites that suggest formation in the interstellar medium. Mass-independent stable isotopic fractionations are the bases of key insights from elements such as O, Mg, Si, Ca, Ti, Cr, and Mo; these are described in the context of important cosmochemical concepts such as CO self-shielding in the proto-solar molecular cloud, and the dichotomy between carbonaceous chondrite (CC) and non-carbonaceous chondrite (NC) groups.

A pair of chapters provides the basis of radioisotopes as chronometers and the resulting chronology of the solar system. The fundamentals of radiometric age dating, conventions, and definitions (e.g., Ma vs. Myr; “age” vs. “date”), and the criteria for when a radioactive system can be applied are all provided. The prior treatment of fractionation of elements provides important context. Both long-lived (K-Ar, Rb-Sr, Sm-Nd, U-Th-Pb, Re-Os, Lu-Hf) and short-lived (I-Xe, Al-Mg, Ca-K, Mn-Cr, Fe-Ni, Pd-Ag, Hf-W, Be-B) radionuclides are discussed. In most cases, brief historical context and applications to cosmochemistry including reservoir evolution (in addition to geochronology) are provided. This chapter alone is a useful reference on par with Faure (1986, *Isotope Geology*, Wiley) in terms of utility.

Among my favorite topics—and something that I have my students construct in my course—is a chronology of the early solar system from long-lived and short-lived chronometric systems applied to a range of meteorite and planetary sample types. The chapter on the chronology of the solar system starts with a fascinating discussion of the implications of the initial abundances of short-lived radionuclides—inferred from meteorites and tabulated in the previous chapter—for the source of these radionuclides and the environment in which the solar system formed. The authors show that these are consistent with our solar system forming in a cluster (such as the Orion nebula), with a supernova or Wolf-Rayet source for the radionuclides, injected into the pre-Sun molecular cloud shortly before (or simultaneous with) collapse and star formation. This is followed by a detailed overview of the main stages of solar system formation, based on astrophysical modeling and observed stellar objects, then the heart of it: linking the absolute ages from long-lived chronometers and the relative ages from the short-lived chronometers to establish a self-consistent timeline of events, including “time zero” for the solar system from CAIs (which formed over a mere 30,000 years), chondrule formation 1–3 Myr after CAIs, the timing of aqueous alteration of carbonaceous chondrites, and the accretion and differentiation of achondrite parent bodies. Other methods including dating planetary surfaces by crater density and cosmic ray exposure ages are also detailed.

Planetesimals are defined in a conventional way—they are the building blocks of the planets—but then asteroids and the icy KBOs are considered as leftover planetesimals, as “unused planetary building blocks” in their own chapter. This enables the authors to incorporate mission results from spacecraft that have explored asteroids (and most recently, returned samples from them), comets, and KBOs. The spectroscopy and taxonomy of asteroids is discussed, and links made between these types and different meteorite types, as shown in a handy figure and table; an overview of the distribution of asteroids in the main belt is provided. Crucial observations of cometary dust collected by the NASA Stardust mission are put into context. The last section discusses thermal metamorphism of planetesimals with and without ice, and melting and differentiation; this places the various types of meteorites into their probable parent body context—including the “onion shell” for chondrite petrologic types. The next chapter builds on this one, and considers the bulk-chemical composition of various meteorites and IDPs alongside results from spacecraft exploration of asteroids including Ceres and Vesta (the latter thought to be the source of most howardite-eucrite-diogenite, HED, type meteorites). Tables of representative bulk compositions of various meteorite groups are notable and potentially useful for student exercises to consider the mechanisms responsible for differences among different meteorite groups (and thus differences between their parent planetesimals).

In the penultimate chapter, the past and ongoing exploration of the Moon and Mars are treated as examples of where much of the exploration of other planets is going: namely, the return of samples from known locations, with mapping from orbiting spacecraft providing context. The history of exploration and the geochemical evolution of the Moon are well summarized in a few short pages using a handful of key diagrams. Data sources for the composition of the crust of Mars are summarized, including orbiting and landed spacecraft and meteorites. A fundamental observation in recent years is the contrast between the samples we have—the martian meteorites—and the compositions of igneous (and other) rocks analyzed at the surface of Mars. This section elucidates this contrast well and suggests some reasons for it; however, solving this conundrum likely requires analyses of carefully selected martian samples in which the geologic context is preserved, such as those recently collected by the Perseverance rover in Jezero crater. Sedimentary processes on Mars, especially chemical weathering, are summarized based on rover data and contrasted with typical processes on Earth. The chapter concludes with an overview of the geochemical evolution of Mars based on the diverse datasets. Together with the Moon's history, the chapter provides two prime examples where the cosmochemistry of the samples constrains planetary geochemical history.

The textbook culminates with a chapter that outlines how cosmochemistry constrains and tests models for solar system formation. With the other chapters providing the fundamental concepts, this chapter reviews the current thinking—including uncertainties—in our understanding of how the solar system formed. Whether the solar system formed as a result of supernova trigger, the shortcomings of the hot nebula model, the role of pebble accretion in the formation of the planets, localized heating events in the nebula and the origin of CAIs and chondrules, astronomical observations of protoplanetary disks, the bulk compositions of the planets (including Earth), collisional histories of Mercury and the Moon, and models involving giant planet migration and scattering of planetesimals—are all discussed. The CC/NC isotopic dichotomy—one of the most significant recent findings in cosmochemistry—is reviewed, with some alternative explanations provided for the student to consider. Lastly, the chapter includes methods for inferring the compositions of exoplanets and makes the point that such works draw heavily on our knowledge of the cosmochemistry of our solar system. Thus, the connections between cosmochemistry and astronomy and astrophysics are further solidified.

It would be effectively impossible for any textbook to capture the current state of cosmochemistry, given the pace of discovery. The authors of *Cosmochemistry* (2022) acknowledge that their book is a snapshot. However, they have done an admirable job of providing context for the ongoing research in this field, and the current and anticipated results from the exploration of the solar system by spacecraft, including returned samples from asteroids, the Moon, and Mars.

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