COSMOCHEMISTRY

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Contents

Summary

Cosmochemistry is concerned with the origin, distribution, and behavior of chemical elements in the universe. Cosmochemistry studies stars, the Sun, Earth, and planetary materials (lunar samples, meteorites, and cosmic dust) with respect to their chemical and isotope composition. Though a theoretical discipline it has implications for applied disciplines.

Cosmochemistry studies the evolution of the universe from the origin of elements through the formation and origin of stars and their planetary systems up to consequent fractionation and cycling of chemical elements in stars and planets.

Cosmochemistry is a highly interdisciplinary subject which uses theoretical, experimental, observational, and analytical methods: astrophysics, astronomical observations, spectroscopy in all wavelengths of electromagnetic spectra, and a wide range of methods used in material science.

The ultimate goal of cosmochemistry is to provide a synthesis of theory, observation, experiments, and analytical data for the evolution of the Universe, the solar system, and Earth and its environment. Overlaps of cosmochemistry and geochemistry make the two disciplines indivisible.

1. Introduction

Mineral deposits that contain sufficient amount of zinc and cadmium are the result of cosmochemical and geochemical fractionation and evolution of material objects in the universe. The production of mineral resources stems from a number of geochemical and cosmochemical processes such as formation of hydrothermal solutions, their precipitation, magma formation, differentiation of Earth into crust, mantle, and core, accretion of planetesimals to form Earth, formation of planetesimals from a solar nebulae cloud (see *Solar System*), and finally, the earliest formation of elements in a supernova. Humans themselves are a result of such chemical fractionation and evolution.

Cosmochemistry is a highly interdisciplinary discipline. It searches for clues to our cosmic roots including answers to questions such as: How were concentration of metals formed? What was the primary original (nonfractionated) material? How did the first galaxies form? How do stars and planetary systems form? Are there any planets outside our solar system? What is their composition? Are they capable of sustaining life? How did life originate on Earth? Is there life (however primitive or evolved) outside our solar system?

Although cosmochemistry is generally understood to be part of geochemistry, such distinction is a semantic confusion. Geochemistry (geo pertaining to Earth) is an older and better formulated discipline than cosmochemistry. Methods used in geochemical research are used to study cosmic materials (meteorites).

Cosmochemistry is the study of the distribution of the elements and their isotopes in the cosmos. Galaxies, stars, clouds, clumps, dust, planetary systems, planets, and planetesimals are part of that cosmos. Earth is part of the solar system. Cosmochemistry thus relates to the studies of Earth and its complex systems.

As an interdisciplinary field, cosmochemistry relies on numerous sources of data. For distant cosmos, sources of information include theoretical and particle physics, astrophysics, spectroscopy, and observations of stars and galaxies in visible as well as invisible parts of the electromagnetic spectra (gamma, x-ray, ultraviolet, infrared, and radio waves). For the cosmochemical studies of closer parts of the Universe, such as our solar system, the major source of data are observations in the visible part of the spectrum (observations through the optical telescopes), remote sensing data in different wavelengths, and chemical (isotopic) and phase studies of planetary (Martian meteorite, SNC), planetesimal (meteorites), terrestrial, and lunar samples. Recent years have provided an enormous database collected by satellites traveling through the solar system.

The scale on which cosmochemistry studies the cosmos varies from the subatomic to the galactic. The ultimate goal of cosmochemistry is the synthesis of data from different fields and sources to provide a complete account of the evolution of Earth, the planets, the Sun, the stars, and the cosmos as well as humans.

2. Origin of the Elements

2.1. Big Bang Event

Chemical elements in the Universe result from several different processes. The Big Bang, which dates some 15–20 Ga produced the light elements H and its isotope deuterium, He, and Li. The support for the Hot Big Bang theory comes from the existence of 3-K microwave background radiation and from abundances of He and Li in the galactic halo.

Astrophysicists will state that the first three minutes after the Big Bang in the history of the formation of chemical elements at the beginning of the Universe are the most important and most interesting events of cosmochemistry. The standard Hot Big Bang hypothesis is elegantly described by Steven Weinberg in popular science books such as “The First Three Minutes: A Modern View of the Origin of the Universe” and/or by S. Hawking in his book “Short history of time”.

The Standard Hot Big Bang theory explains the formation of H and He (and Li), which are by far the most abundant elements in the Universe. The synthesis of less abundant and heavier elements takes place in later events of the evolution of the Universe.

Cosmochemistry deals with the formation of heavier elements in supernovas up to the formation of solid material in the molecular, diffusion, and protoplanetary clouds. The studies of planetary materials (e.g., meteorites, interplanetary dust particles (IDPs)) as well as theoretical studies including nuclear physics, astronomy, and astrophysics contribute to knowledge of nucleosynthesis in solar system abundances.

2.2. The Chemistry of Star Formation

The onset of the chemistry at the start of this process is due to the formation of H_2, believed to result from the interaction of atomic hydrogen gas with dust grains. The process is not well understood, partly because of the uncertainty associated with the nature of the dust surfaces.

Analysis of stellar and nebular spectra has provided data on the composition of stars and galaxies and the composition of gases and dust that fills the space. During the last quarter of the twentieth century, chemists have responded to the challenges raised by astronomers in their attempts to understand the variety of molecules detected in interstellar clouds. Observations have shown the chemistry of these regions to be surprisingly complex, and now more than one hundred molecular species have been identified in interstellar and circumstellar regions of our galaxy. The chemistry of the interstellar clouds that give rise to these molecules is now believed to be reasonably well understood in terms of a network of some thousands of binary reactions between several hundred species.

In the 1970s and 1980s a concerted effort was made by experimental and theoretical chemists to solve problems identified by astronomers of gas-phase chemistry in interstellar clouds.

Interstellar gas in our galaxy is distributed in an irregular fashion, in clouds of various sizes. Much of the mass is encompassed in so-called giant molecular clouds (GMCs) which range in mass from about 10^4 to about 10^6 solar masses (the solar mass is about 210^{30} kg). A study of one particular GMC, the Rosette molecular cloud (RMC), shows that it contains almost 210^5 solar masses of gas, extending over 100 light years. The gas in the RMC is fragmented into about 70 clumps with masses ranging from a few tens to a few thousands of solar masses. The clumps are embedded in a more tenuous medium, typically contain 10^2–10^3 H_2 molecule cm^{-3}, and are cool (<30 K). Observations show that clumps with larger column densities of CO (>10^{16} CO molecules cm^{-2}) are more likely to contain embedded stars.

Astronomers are attempting to interpret observations of star-forming regions. These regions are much more complex in physical terms than quiescent interstellar clouds. In star-forming regions, interstellar gas is being compressed, the force of gravity is overcoming the resistance provided by gas pressure, and forces such as magnetohydrodynamic turbulence, magnetic pressure, and rotation play an important role. The chemistry is not in a steady state during this collapse, and can therefore be used as a tracer of the evolution of the collapse of interstellar gas.

Collapse of a clump leads to fragmentation and the formation of a cluster of dense cores. Species of lower abundance than $^{12}C^{16}O$ can trace the dense gas in cores (>10^4 H_2 molecules cm^{-3}), and they include NH_3, CN, H_2CO, and CS.

2.3. Stars, Novae, and Supernovae

The light elements of hydrogen, helium, and lithium were produced in the Hot Big Bang event. The heavier elements were produced (and are produced) over time by processes involving the evolution, burning, and destruction of stars, and by processes in novae and supernovae.

Processes in stars are characterized by the outputs of energy. The fusion reactions, which fuse two nuclei together, are responsible for the origin of elements heavier than hydrogen. Two protons can be joined in this way to form a single larger nucleus, with a large amount of energy released. Since the protons, the nuclei of hydrogen, are most abundant species in the universe, the fusion of protons is a main source of energy and their fusion into deuteron (nuclei of deuterium) and the proton–deuteron reaction leads to formation of helium

$$p + d = {}^{3}\mathrm{He} + \gamma \qquad (1)$$

Also, the proton–proton cycle leads to helium

$$4p = {}^{4}\mathrm{He} + 2e^{+} + 2\nu + 2\gamma \qquad (2)$$

Such processes indicate that the concentration of helium in stars steadily increases. In most ordinary stars—like our Sun—nucleosynthetic processes are represented by the syntheses of protons (hydrogen nuclei) to produce helium. Helium nuclei then collide and the heavier elements such as beryllium are formed.

$${}^{4}\mathrm{He} + {}^{4}\mathrm{He} = {}^{8}\mathrm{Be} \qquad (3)$$

Since the beryllium is unstable, it reacts with helium to form carbon

$${}^{4}\mathrm{He} + {}^{8}\mathrm{Be} = {}^{12}\mathrm{C} + \gamma \qquad (4)$$

or

$${}^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} = {}^{12}\mathrm{C} + \gamma \qquad (5)$$

and carbon reacts with helium to form oxygen.

$${}^{4}\mathrm{He} + {}^{12}\mathrm{C} = {}^{16}\mathrm{O} + \gamma \qquad (6)$$

Other reactions involve the formation of elements through the fusion of protons with elements such as C, O, F, or Si, or by the collisions of heavy nuclei of the same type,

$$12\mathrm{C} + 12\mathrm{C} = 23\mathrm{Na} + p \qquad (7)$$

or through the collisions of heavy nuclei of different type.

$$12\mathrm{C} + 16\mathrm{O} = 28\mathrm{Si} \qquad (8)$$

The above reactions were predicted in the past by nuclear physicists. However, in t 1987 observations were made. Supernova 1987a provided direct (spectral) evidence of element synthesis (synthesis of radiogenic 56Co, 56Ni), and decay of those unstable isotope species into stable 56Fe was observed.

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Biographical Sketch

Dr Petr Jakes, is a researcher at the Institute of Geochemistry, Mineralogy, and Mineral in the Faculty of Sciences, Charles University in Prague, Czech Republic. Jakes graduated with MSc in Economic Geology from Charles University in 1962 and got his PhD in 1970 from the Australian National University. Since then, he has been a postgraduate scholar at the University of Kanazawa, Japan, and at the Lunar and Planetary Institute in Houston. Later he worked as a field geologist for the Geological Survey in Prague and was geochemistry branch chief and head of reasearch there. He has been a visiting professor at Kyoto University and the University of Houston and was also a visiting scientist at the Lunar and Planetary Institute in Houston (1990–1992), and an invited professor at UMPC in Paris for one semester). His major interests are the geochemistry and petrology of Earth and planetary materials and mineral resources. Jakes also writes popular science books and articles and produces popular science TV programs.