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Hydrogen Loss and the Evolution of Planetary Redox States

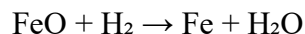
One of the most important factors controlling planetary chemistry is the abundance of hydrogen. Hydrogen strongly influences whether a planetary environment behaves as chemically **reducing** or **oxidizing**, and changes in hydrogen abundance over time can significantly alter the chemical state of a planetary body. Because hydrogen is both highly reactive and easily lost to space, gradual hydrogen depletion may play an important role in the long-term evolution of astronomical objects.

Within the framework of the **General Theory of Stellar Metamorphosis**, hydrogen loss is interpreted as part of a broader evolutionary process in which hot stellar objects gradually cool and transform into colder bodies. In this view, stars begin as extremely hot, hydrogen-rich objects and, over very long timescales, cool and evolve into their colder counterparts—objects that we classify as planets. From this perspective, hydrogen abundance is highest in the youngest stellar bodies and decreases as these bodies evolve thermally and chemically.

Hydrogen as a Reducing Agent in Planetary Chemistry

Hydrogen is among the strongest reducing agents present in planetary systems. In geochemical terms, a reducing environment is one in which oxygen is readily removed from compounds, while an oxidizing environment is one in which oxygen remains chemically available to bind with other elements.

When hydrogen is abundant, it tends to remove oxygen from minerals and compounds through chemical reactions. A simple example illustrates this process:



In this reaction, iron oxide is reduced to metallic iron while hydrogen combines with oxygen to form water. The chemical effect is that oxygen is removed from the mineral phase and captured in water molecules. As a result, environments rich in hydrogen tend to maintain strongly reducing chemical conditions. Conversely, when hydrogen becomes scarce, oxygen remains bound within minerals or becomes available for new oxidizing reactions, producing a more oxidized environment.

Hydrogen in Early Stellar and Planetary Bodies

Large astronomical bodies contain enormous quantities of hydrogen. Gas giants such as **Jupiter** and **Saturn** are composed primarily of hydrogen and helium, demonstrating how dominant hydrogen can be in massive planetary objects.

In the Stellar Metamorphosis framework, this hydrogen-rich state reflects an earlier evolutionary phase that is closer to stellar conditions. Younger stellar objects are thought to contain even greater quantities of hydrogen, which gradually decline as the object cools and evolves. Over time, hydrogen escapes from the system through a variety of physical processes, gradually transforming the chemical environment.

Even planets that are now rocky may once have contained far greater amounts of hydrogen than they do today. Hydrogen can exist in several forms within planetary interiors and atmospheres. It may dissolve into molten rock during magma ocean phases, become incorporated into water, form metal hydrides in planetary cores, or accumulate as atmospheric hydrogen gas. When present in large quantities, hydrogen maintains reducing conditions within the planetary environment.

Mechanisms of Hydrogen Loss

Despite its chemical importance, hydrogen is also the element most easily lost from planetary bodies. Because hydrogen atoms are extremely light, they can escape planetary gravity more readily than heavier elements. Over long timescales, several mechanisms contribute to the gradual escape of hydrogen into space.

One important mechanism is **thermal escape**, in which energetic hydrogen atoms in the upper atmosphere reach velocities exceeding a planet's escape velocity. Another process is **solar wind stripping**, where charged particles emitted by the Sun interact with a planet's atmosphere and remove hydrogen ions. Ultraviolet radiation can also break apart water molecules through **photodissociation**, splitting H₂O into hydrogen and oxygen. The hydrogen then escapes to space while the oxygen remains behind.

These processes are thought to have played major roles in the atmospheric evolution of planets such as **Mars** and **Venus**, where substantial hydrogen loss is believed to have occurred over geological time.

Hydrogen Loss and Increasing Oxygen Fugacity

The gradual loss of hydrogen has an important chemical consequence: it changes the **oxygen fugacity** of the environment. Oxygen fugacity is a measure used in geochemistry to describe the availability of oxygen for chemical reactions.

When hydrogen is removed from a planetary system while oxygen remains, the chemical environment naturally shifts toward more oxidizing conditions. Early in planetary evolution, when hydrogen is abundant, metallic iron and sulfide minerals are stable and oxygen fugacity is extremely low. As hydrogen gradually escapes, some iron becomes oxidized and silicate minerals dominate. In later stages, when hydrogen has been largely depleted, iron oxides and hydrated minerals become stable phases.

Thus, the simple removal of hydrogen from a system can progressively shift the redox balance toward higher oxygen fugacity.

Meteorite Diversity and Redox Conditions

Some researchers have suggested that variations in meteorite composition may reflect different redox environments during planetary evolution. Certain meteorite groups exhibit mineral assemblages that indicate very reducing conditions, while others formed under more oxidizing conditions.

For example, **Enstatite chondrite** meteorites contain minerals that appear to have formed under extremely hydrogen-rich and highly reducing conditions. **Ordinary chondrite** meteorites reflect intermediate redox conditions, while **Carbonaceous chondrite** meteorites generally show evidence of more oxidized environments.

One interpretation is that these meteorites may represent materials formed during different stages of hydrogen depletion and oxidation. Some proponents also suggest that many meteorites may originate from fragments of ancient planetary bodies that were later destroyed. This concept has been explored in speculative frameworks such as the **Krypton Hypothesis**, which proposes that meteorites may be remnants of long-since disrupted worlds.

Planetary Evolution Through Hydrogen Loss

Within broader planetary evolution models inspired by Stellar Metamorphosis, gradual hydrogen loss is viewed as a major driver of planetary transformation. In this view, bodies may begin as hot, hydrogen-rich stellar objects. As they radiate energy and cool over immense timescales, hydrogen gradually escapes, increasing oxygen fugacity and altering the chemistry of the interior.

Through this process, objects may evolve from stellar states toward hydrogen-dominated gas giants and eventually toward more oxidized rocky planets.

Bodies such as **Jupiter**, **Saturn**, **Uranus**, **Neptune**, and **Earth** are therefore sometimes discussed as representing different stages along this broader thermochemical evolutionary pathway.

Timescales for Hydrogen Loss

The evolution of planetary redox chemistry may occur over extremely long timescales. Large self-gravitating bodies possess significant **thermal inertia**, meaning they retain internal heat for billions of years. This long-lived internal heat allows chemical reactions to continue within planetary interiors while volatile components slowly escape to space.

Because these processes occur gradually, changes in hydrogen abundance—and therefore oxygen fugacity—could potentially unfold over geological time periods spanning billions of years.

Conclusion

Hydrogen plays a fundamental role in controlling planetary redox chemistry. When hydrogen is abundant, planetary environments tend to remain strongly reducing. However, because hydrogen is easily lost to space, planetary bodies may gradually experience hydrogen depletion over time.

If hydrogen escapes while oxygen remains, the chemical environment naturally shifts toward increasingly oxidizing conditions. Within the framework of the General Theory of Stellar Metamorphosis, this gradual loss of hydrogen is interpreted as part of a broader evolutionary pathway in which hot hydrogen-rich stars cool and evolve into colder planetary bodies. In this interpretation, progressive hydrogen loss drives long-term chemical and structural transformations that accompany the transition from stellar to planetary states.