COSMIC WATER

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Once believed by science to be the substance that distinguished Earth from the rest of the universe, it is now understood that water is ubiquitous in the cosmos—not only as ice and vapor, but perhaps also as liquid. Sophisticated scientific instruments are able to detect cosmic water on the basis of the light, or other electromagnetic, waves that it emits.[1] Unlike the legendary "waters of chaos" that gave rise to the material world, water's component hydrogen and oxygen atoms owe their existence to the Big Bang and to the stars, respectively.

HYDROGEN AND OXYGEN

Hydrogen is both the simplest and the most abundant atom in the universe, representing about 75% of the atomic mass in the cosmos. The word *hydrogen* literally means "water-forming" according to the Greek language from which it is derived. Hydrogen atoms are generally traced back to the so-called Big Bang, when a tremendous amount of energy was released and subsequently expanded into what we call our universe. As the newborn universe began to cool, subatomic and atomic particles (e.g., quarks, protons, electrons) were initially created and later drawn together by a number of fundamental forces to form atoms. Possessing one proton and one electron, hydrogen is believed to have been the first atom created. As more hydrogen atoms were created in the early universe, they coalesced into dense gas clouds that contained much of the conventional matter.

Oxygen is the third most abundant atom in the cosmos—behind hydrogen and helium. Because helium is a very inert (non-reactive) atom, water is sometimes described as an interaction between the two most abundant "reactive" atoms in the cosmos. Unlike hydrogen, the origins of the oxygen atom are rooted in dying stars rather than in the Big Bang. As stars near the end of their stellar life, they begin to cool and to switch from hydrogen to helium as a source for nuclear fusion. The cooling stars then enter a phase where they become increasingly dense as intense gravitational energy compresses them into an extremely unstable state that may explode during the final stages of compression.[2] This explosion or *supernova* releases the outer layer of the star, which contains many common atoms (e.g., oxygen, carbon), into space as interstellar clouds. Dust grains comprising these clouds are composed of silicate (oxygen-rich) and carbonaceous (carbon-rich) minerals that are available to react with hydrogen to form simple molecules.[1]

INTERSTELLAR SPACE

In the interstellar realms of galaxies, water exists predominantly as ice—adhering to the tiny particles that comprise the ubiquitous dust and gas clouds. Water is the primary molecular ice attached to these particles, although methane, carbon monoxide, and water-ammonia mixtures may also be present depending on physical conditions in the gas clouds.[3] Water ice present in the 10^{o} K temperatures and vacuum conditions of interstellar space is what physical chemists refer to as *amorphous ice* or *glassy water*, which is relatively unstructured compared to the highly crystalline ices that are formed at higher temperatures (e.g., those characteristic of Earth's surface and atmosphere). In fact, amorphous ice is so unstructured that it is actually able to flow, not unlike a viscous version of liquid water.[4] Some astrophysicists posit that the simple organic molecules responsible for biological life may have been created in this strange ice.[4] As interstellar temperatures rise above 150^{o} K (as often occurs near stars) amorphous ice irreversibly transitions to the more familiar crystalline ice.

Although water's component atoms are plentiful in interstellar dust and gas clouds, it appears that creation of molecular water requires either that O and OH species be converted directly to water ice on the surfaces of dust grains or that water vapor be produce via heat energy−usually in the form of stellar radiation.[5] The latter process requires that water vapor adhere to dust grains, where the newly formed water molecule is protected from the same ionizing radiation that created it. Scientists currently believe that stars not only facilitate that creation of water vapor, but also that water vapor assists in the birthing of stars. Stars are being born and dying on an ongoing basis, such that star birthing regions (e.g., the Orion Cloud Complex of the Milky Way Galaxy) generate up to 20% of a galaxy's luminosity as gas and dust clouds are gravitationally compressed into newborn stars. Recent data indicate that these cloud complexes contain an extremely high concentration of water vapor, which has been estimated on the order of 1 part in 2000.[6] The super-abundance of water in stellar nurseries (about 20 times greater than that in similar interstellar clouds) may permit the gas and dust to cool sufficiently so that condensation can proceed and stars are eventually formed.

As hot winds (in the form of shock waves) are sent out during the stellar birthing process, the cloud must be cooled—initially by molecular hydrogen and subsequently by water and other simple gases.[7] Water vapor is created during the interstellar cloud shocks as oxygen reacts explosively with hydrogen, causing the water vapor concentration to increase substantially during the star-birthing process. Scientists have theorized one of two eventual fates for water created in the star-birthing process. One is that the intense heat of the fledgling star rapidly dissociates water into its component atoms. The other is that the water is deposited on dust grains that later form the star's planetoids. The origin of earthly water is usually attributed either to this second process or to the impact of large comets, which are believed to have been more prevalent during Earth's early history.

STARS

Two of the brightest supergiants in our galaxy, Betelgeuse and Antares, were discovered to actually have water in their *photosphere*, which constitutes the visible portion of a star.[8] A star's photosphere is where its gases transition from opaque to transparent, permitting us to see the stars that are located closest to Earth. This stellar water is actually present within the star itself and not just as a component of the surrounding dust and gas cloud from which the star was birthed. Aging supergiant stars have been observed to release massive amounts of water as they die; however, the exact source and role of this water is not yet known.

In addition to cool stars, water has been discovered in the photosphere of at least one hot or *main sequence* star—namely, the Sun. Although water cannot exist on the surface of the Sun, where temperatures of 6000° K dissociate the water molecule into its component hydrogen and oxygen atoms, water can exist in the dark centers of sunspots, where temperatures are less than 3500° K.[9] Sunspots are relatively calm solar regions where strong magnetic fields filter out the energy emanating from the intense interior, rendering them both the coolest and darkest regions of the Sun. Water is a major player in determining a star's *radiative opacity*, which describes the extent to which light escapes from stars into interstellar space.[10] Water essentially impedes the outward flow of radiation from stars by absorbing energy within certain wavelengths and, thus, renders the star more opaque that it would otherwise appear.

COMETS AND METEORS

Comets are one of the few interstellar objects that are commonly associated with water, predominantly in the form of ice. Comets are composed primarily of water ice that incorporates many of the other simple molecules in interstellar dust and gas clouds (e.g., carbon monoxide, methane, ammonia). Comets are most easily recognized by their unmistakable tails, which can extend millions to hundreds of millions of kilometers behind the icy body of the comet. The tail consists of dust and ionized particles (mostly water ice) that are always transported away from the Sun by the *solar wind*. The solar wind is an ionized stream of particles consisting predominantly of protons and electrons that are released from sunspots. The ionization of water ices is the primary mechanism influencing the properties of a comet's tail, including the steam jets that release tons of water vapor per second from the comet. It is now believed that these steam jets are a result of solar-induced changes to ice's molecular geometry, transitioning from an amorphous to a crystalline structure. While large comets are generally accepted as a source of planetary water, controversy surrounds the hypothesis that a constant barrage of small comets hitting the planet's upper atmosphere also contributes significantly to the volume of water on Earth.

The first liquid water in the Solar System was projected to have made its appearance on meteors just twenty million years after our Sun and its debris emerged from the interstellar dust and gas cloud.[11] Although liquid water is rarely present on the surface of meteors today, the chemical interaction of water with primitive rocks produced carbonate minerals, suggesting that the chemical processes of water evaporation and condensation were among the earliest in the solar system. Recently, a small meteorite found in southwestern North America contained actual liquid water within its salt crystals, which were believed to have been created from the original interstellar cloud that gave rise to the solar system.

PLANETOIDS

Most planet-sized bodies in our solar system (and probably in others) are now known or suspected to contain water in some form. A number of recent missions have revealed a Martian landscape that almost certainly indicates the large-scale flow of liquid water. Not only do the surface features of Mars (e.g., flood plains, river beds, mud deposits) suggest the recent presence of liquid water, but also the mineralogy of Martian rocks could only have resulted from aqueous processes. Moreover, it has been hypothesized that Mars may have also once possessed surface oceans. The Jovian moon, Europa, is another of the solar system planetoids that probably contains liquid water located tens of kilometers beneath its icy surface. The liquid water underlying Europa's surface ice is believed to be an ocean containing saltwater that may be similar in composition to the seawater of Earth's oceans. Unlike Earth, the heat required to maintain water in a liquid phase on Europa is believed to originate from an internal source such as volcanic activity rather than from the heat of the Sun.

Data collected from the Infrared Space Observatory indicate the presence of water in the upper atmospheres of our solar system's gas giant planets and on one of Saturn's moons.[1] The source of water in these planet's atmospheres is attributed to comets or to water-containing interplanetary dust. Based on recent techniques for measuring a suite of stellar characteristics (e.g., orbital velocity, position, brightness), the search for planets has been extended beyond our solar system to other star systems in the galaxy.[12] Various planets have been identified orbiting stars in the constellations of Leo, Pegasus, Virgo and Ursa Major that probably possess surface temperatures ranging from slightly less than 100^o C down to -100^o C. Planets or moons characterized by this temperature range could potentially possess water in solid, gaseous, and liquid phases.

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