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The rise of hydrological science off Earth

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SUMMARY

It has been a long lasting interest to understand the laws that underlie water movement on Earth with the purpose to control it and make use of it. It is now recognized that water is not exclusive to the Earth but, rather, is a major constituent of the matter in the universe and may be a proxy for life in other planets as well. In this paper, we reflect on the need to expand the boundaries of the current water sciences from the description of mere terrestrial hydrological processes to a comprehensive inclusion of the physical laws and processes pertaining to water dynamics off Earth. Are we at the edge of a new scope of hydrology?

1. Introduction

Water has been considered one of the elementary substances in all ancient cultures, but it is only since the European renaissance that empirical approaches were attempted to understand the laws that describe its movement in our environment (e.g., Giovan Fontana, c.a. 1395–1455; Leonardo da Vinci, 1452–1519; Geronimo Cardano, 1501–1576; Bernard Palissy, 1510–1589)[1]. Once the physical principles of the terrestrial water cycle had been postulated (e.g., Pierre Perrault, 1608–1680), the approach to hydrology became scientific, i.e., it became possible to measure processes, to test hypotheses and to repeat experiences (Galileo Galilei, 1564–1642). Hydrology then took a modern form following the contribution of many among whom Benedetto Castelli (1577–1644), Henry Darcy (1803–1858), Robert Manning (1816–1897), Lorenzo Richards (1904–1993), and others (we refer the readers to the comprehensive history of hydrology narrated by Biswas (1970)). Over the past few decades, the development of electronic sensors and technologies made possible to record systematically many hydrological processes with unprecedented precision and sampling frequency. Together with the increasing availability of data, the capability to process observational data and refine our theories has enormously improved thanks to the development of computers.

Whereas observing, characterizing and modelling hydrological processes is easier now than it was 20 or 100 years ago, we believe that the blooming of hydrological informatics has not yet exhausted the scope of hydrology. Indeed, our picture of the water cycle is as comprehensive in relation to our immediate environment on Earth as it is incomplete if we expand our view to beyond the Earth. Where does water originate from? How did water accumulate on Earth? And, how is the terrestrial water budget evolving at planetary time scales? These questions have been formulated earlier (e.g., Kotwicki, 1991) but they have never been contextualized in the framework of classical hydrology. On the other hand, finding water in the universe, specifically on planets of this and other solar systems, has become the target of modern space exploration programs. One reason motivating this search is that water is widely accepted to be the proxy for life and, as such, it is the one major substance that may provide us with evidence of primordial or developed extraterrestrial life forms (e.g., of ESA-EANA network and NASA-Astrobiology). The information obtained by space observation and exploration only marginally answers the questions stated above. However, such information can stimulate our reasoning further and can lead to a great deal of brand-new challenges to classical terrestrial hydrology. As a matter of fact, we have not yet approached the fundamentals of water movement and cycling off Earth, its interactions with our planet and others, and its potential implications for the universe evolution, including life. The whole body of knowledge on the hydrologic cycle man commands

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[1] Evidence of systematic meteorological measurements appeared as early as 1200 B.C. in Asian civilizations (UNESCO, 1974) but these independent thinking of hydrology did not directly influence the later Europeans.

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to date is so empirical and fine-tuned to the Earth's, that we have only a poor understanding of water dynamics in space and its interactions with astronomical bodies, in environments very different than those found on Earth. Facing these new challenges invokes expanding the current hydrology domain from the description of mere terrestrial processes to a comprehensive inclusion of physical laws and processes pertaining to water dynamics off Earth. These challenges set a new scope for hydrology, which may be best described by the word *astrohydrology*. Why and how could astrohydrology become important? Astrohydrology may reveal particularly useful to understand specific water-related processes contributing to the evolution of planets or satellites (e.g., Earth, Mars and the Moon), to understand the environmental conditions under which life could take place (e.g., the "habitable zone"), and to support manned exploration of space and planets.

In this work, we delineate the rationale of extending the scope of hydrology beyond the Earth's horizon upon the existing evidence of hydrological aspects on other celestial bodies. Along this line, we will discuss the need to define a hydrologic cycle off Earth and we will provide a conceptual representation of it. Quantitative approaches will be limited to simplistic analyzes, with no pretention to derive a general theory. However, we intend to stimulate the reader's way of thinking about the current scope of hydrology and possibly expand it toward astronomical bodies.

2. Evidence of extraplanetary hydrology

It has been recognized only relatively recently that water is not exclusive to Earth but is plentiful in the universe. Space observation and exploration confirms that water is present and abundant on celestial bodies such as Mars (e.g., Grotzinger, 2009) and Venus (e.g., Kasting, 1988; Svedhem et al., 2007), in the Lunar crust (e.g., Hand, 2009) and other exoplanets (e.g., Knutson, 2007), comets and meteorites (e.g., Deming, 2008). These observations of the presence of water off Earth ask for new reflections on the limits of the current scope of hydrology and on the need to consider the existence of a hydrologic cycle in space.

The one example that has received a particular attention is the hydrologic cycle on Mars. The surface of Mars has been described since the 19th century when Schiaparelli described and commented a number of visible surface features (Schiaparelli, 1893). Since the 1960s, extraordinary observational data became available from the Martian orbiters and the later landers (e.g., Baker, 2007), clearly showing neither signs of organized hydrological infrastructures nor signs of civilization. Regardless of any references to potential Martian life forms, there is now a general consensus on paleoclimatic reconstructions indicating that Mars was warmer than today millions of years ago, and that liquid water must have been present in rivers, lakes and seas. Surface water was likely fed by springs and ice caps; evidence of hydrological processes have been inferred from geomorphologic features such as channels, valleys, eroded beds, and fluvial deposits, all tightly resembling the geomorphology of water-exposed land on Earth (Kargel, 2004). Clay mineral formation has also been reported as an evidence of long-duration interaction between water and rock (e.g., Ehlmann et al., 2011). It has been more difficult, however, to elaborate on the frequency and intensity of hydrological processes that specifically caused such features. For example, the flow discharge in rivers must have been different than on Earth due to a lower gravity (0.38 g) and to the absence of vegetation. Abrupt large floods have been hypothesized to have caused erosion of giant valleys connected by networks of rivers similar to as on Earth (e.g., Pieri, 1980; Dietrich and Perron, 2006). A relatively active groundwater storage has been suggested to explain the occurrence of evaporite deposits (Andrews-Hanna et al., 2007; Amundson et al., 2008) and the surface erosion due to groundwater sapping (Lamb et al., 2008). It has been suggested that the origin of such groundwater could be the melting of ice from geothermal activity and that groundwater recharge could largely have resulted from precipitations, which might have contributed also to surface erosion by runoff (Craddock and Howard, 2002). So far, however, these hypotheses have been formulated on the basis of our understanding of terrestrial hydrology, but none of them has yet been substantiated firmly. Currently, the surface hydrologic cycle on Mars is dominated by a seasonal migration of water vapor between the poles, which then freezes and precipitates as frost (Kargel, 2004). Surface ice is relatively abundant (Boynton et al., 2002), but it is not fully known if belowground liquid water is currently present as it probably was in the past (Baker, 2007).

Another planet of our solar system that has received an attention in terms of hydrology is Venus. It is hypothesized that, like Mars, Venus was relatively rich in water during its earlier ages (Kasting, 1988). Some evidence of D/H (deuterium/hydrogen) isotopic composition of residual water vapor in its atmosphere indicates that Venus underwent water escape caused by solar radiation (wind) in a similar way to Mars, which eventually resulted in strong water depletion (Grinspoon, 1993; Svedhem et al., 2007). In the case of Venus, however, much less information is available on other hydrological processes occurring at its surface or belowground.

Europa, one of Jupiter's moons, contains abundant water; it is hypothesized that its solid crust floats on a variably deep ocean of mixed liquid-iced water, and gives rise to tide-induced tectonic movements that, more or less periodically, produce fractures and uplift of water to surface, which then freezes (e.g., Gaidos and Nimmo, 2000). This hydrogeological phenomenon has been proposed as a possible explanation for the characteristic cracks and lines visible at its surface. If the presence of a submerged ocean on Europa becomes substantiated, Europa's crust would be a unique hydrogeological system that cannot be compared to terrestrial aquifers, and for which the classical description of belowground water storage and turnover would have to be reviewed profoundly. There is no evidence of a surface hydrologic cycle on Europa, which is too small to possess an atmosphere capable of retaining water.

Given the number of new planets (and potential solar systems) that are continuingly being discovered (e.g., several hundreds since the launch of the NASA Kepler probe in 2009), the variety of hydrological scenarios that may be encountered will increase. This will ultimately require us to consider whether to include astronomical aspects as components of hydrology sciences.

3. Needs for a definition of the hydrological cycle off Earth

Evidence of an evolutionary water cycle on planets in the solar system suggests that water accumulated in celestial bodies undergoes local dynamic cycles and also exchanges with the open space. These characteristics lead us to discuss in more details two key aspects.

First, the concept by which terrestrial hydrology develops through cyclical processes of evaporation, condensation, cloud formation, rainfall, river flow and water storage may fail to describe the water cycle on other planets and celestial bodies. Most water in the universe does not exist in the same geophysical forms and does not occur with the typical hydrological processes that we are familiar with on Earth. Due to astrophysical conditions such as the distance from a source of heat (e.g., a Sun), very few planets have thermodynamic conditions allowing for the presence of liquid water near the temperature and pressure of the triple point, which is peculiar to the hydrologic cycle of Earth. Rather, water on other planets is mostly present in the form of atmospheric vapor and crustal ice, and does not interact with life forms such as vegetation. The absence of liquid water and vegetation does not itself preclude the presence of a cycle in these exotic conditions. For instance, the effects of non-terrestrial gravitational accelerations on convective and advective flows (e.g., in the atmosphere), the effects of atmospheric temperature and pressure on the physical state of water (e.g., in relation to surface hydrology), the interactions with geological strata (e.g., below surface hydrological processes), the effects of thermal and radiative processes, and the implications of the absence of vegetation should be analyzed and mechanistic relations should be sought between the underlying hydrological processes and for time scales in the order of magnitude of the planetary evolution. We should assume that the physical principles of energy, mass, and momentum conservation would hold valid regardless of whether we aim at describing the hydrologic cycle of Earth or of any celestial body. However, we may have to include in our equations terms that we make no use of in terrestrial hydrology, or exclude terms that recur normally. For example, the absence of liquid water on the surface of Mars does not rule out the presence of a relatively important surface–atmosphere water exchange (e.g., through ice sublimation and frost deposition) as long as suitable time and length scales are evoked, but the hydrograph theory of precipitation-to-runoff transformation at the watershed scale would make no sense in this case. A further example may be the slow but persistent removal of water molecules from the Martian atmosphere caused by solar wind, not accounted for in terrestrial hydrology. A final example may be the absence of plant transpiration in off Earth systems, which is an essential component of water fluxes in terrestrial ecosystems.

The second and most important point of discussion is concerned with the mass exchange with open space. Since the beginning of hydrology, it has been tacitly assumed that the water cycle on Earth occurs as in a closed system, thus meaning that any water exchanges are implicitly neglected. This hypothesis may hold in terms of the water budget of Earth on human time scales but may become ill posed for the global water budget on geological and planetary scales. From the examples introduced in Section 2, and in opposition to what assumed for the Earth, we clearly learn that water escape from or accumulation on celestial bodies are major drivers of changes in planetary hydrological and climatic conditions. Relaxation of this assumption implies that hydrological processes in celestial bodies (including the Earth) should be thought as open to water exchange with interplanetary space. The implication of assuming an open hydrological cycle also for the Earth raises new questions such as: where does terrestrial water come from? Where does it go next? And, does water cycles through space? Developing a coherent theoretical structure to frame astrohydrology necessarily invokes a different paradigm to that of "closed hydrology", and consequently, a new paradigm should be sought and tested.

4. A concept of the hydrological cycle in the universe

Following our reasoning above, we relax the assumption of a closed planetary water cycle and we try to address the hydrologic cycle in space. In doing so, we rely on the evidence of various processes that are of interest to frame the hydrologic cycle in the universe and to address this in the least speculative way as possible. However, we recognize that such an objective is ambitious and that large uncertainties remain in nearly all compartments of our conceptual framework.

A hydrological description of the water cycle in the universe must start from the origin of the building elements (H and O) of the water molecule H_2O. After Lamaitre's and Hoyle's work early in the 20th century, the generally accepted theory of the origin of all matter is the "Big Bang". Within nearly a century of investigation, this theory has proven that a singularity event of that type could produce a large amount of hydrogen (H), deuterium (D), and the various isotopes of helium (He) and lithium (Li) currently present in the universe (e.g., Trimble, 1975; Fields and Olive, 2006). This said, the "Big Bang" is not actually included in our representation of the astrohydrologic cycle as it is supposed to be a unique event in the event horizon.

After the "Big Bang", the nucleosynthesis of elements continues today in stars and is accompanied by the synthesis of elements heavier than H among which is atomic oxygen O (Fowler, 1984). We take the nucleosynthesis of elements in stars as the actual starting point to describe the astrohydrologic cycle of water (Fig. 1, icon A). Stellar nucleosynthesis occurs by H burning resulting in He, and He burning resulting in C, N, and O elements along a complex network of nuclear reactions better described in Burbidge et al. (1957) and more recently revisited in Wallerstein et al. (1997). Observations of the atomic composition of the Sun and similar stars returned atomic H abundance between 3 and 4 orders of magnitude higher than that of atomic O (i.e., since Suess and Urey, 1956). More recent observations confirm the higher abundance of H over O atoms but raise the question of how these are distributed within the various regions of a star (e.g., Trimble, 1975). H and He burning takes place originally in the central regions of a star and finally in the shell surrounding that region. Subsequent stages of the burning processes modify the inner part and the early burning stages, thus changing the elemental abundances (e.g., Fowler, 1984). Hence, the rates of nucleosynthesis reactions in the various regions of a star affect and determine the relative composition of its matter. We shall assume that a large amount of H is available in the various shells of stars while O is less abundant in the inner region.

H and O atoms, the latter resulting from burning reactions, are emitted in the interstellar space in various ways depending on the mass and age of the star. Ejection of atoms occurs in a nearly continuous way in the form of solar wind as radiation and flares (Fig. 1, process 1a). For example, the Sun continually loses mass through corpuscular radiation. The mass loss during its life time is negligible in comparison with its total mass ($\sim 2 \times 10^{30}$ kg) but is estimated to be about 2×10^9 kg/s (Kallenrode, 1962). The rate and composition of these emissions in stars are affected by the nuclear reactions and depend on mass, radius, rotational speed and other factors (Stromgren, 1952). From a compilation of observations of various stars, the O/H abundance ratio with respect to the O/H ratio in the solar system shows that stars are slightly depleted in O (Trimble, 1975) and suggests that O atom may be produced not only in stars but also somewhere away from the star surface. Eventually, the evolution of the star and the surface nuclear reactions decide the abundance of elements released in the interstellar medium as solar wind. From the data reviewed in Trimble (1975), we infer an O/H ratio in the range of $(1.5–2) \times 10^{-3}$ for the solar corona and in the range of $(0.75–2) \times 10^{-3}$ for the solar wind.

Massive emissions of H and O atoms from stars to the interstellar space also occur during other phases. For example, when stars approach the final stages of their existence, they release strong radiative emissions, and the mass is lost primarily as H (Cassinelli, 1979). Stars with a mass larger than eight times the Sun mass can end their life with a collapse and explosion by novae and supernovae with ejection of matter, including H and O (Fowler, 1984; Rauscher, 2004). It is argued that supernovae shock waves may induce nuclear reactions responsible for the production of heavier elements than He and Li, such as O, in the surrounding regions (e.g., Trimble, 1975; Wallerstein et al., 1997). Synthesis of O by shockwaves can explain why stellar matter is slightly depleted in O as compared with the surrounding planetary system. The evolution of matter after novae and supernovae is still largely debated but

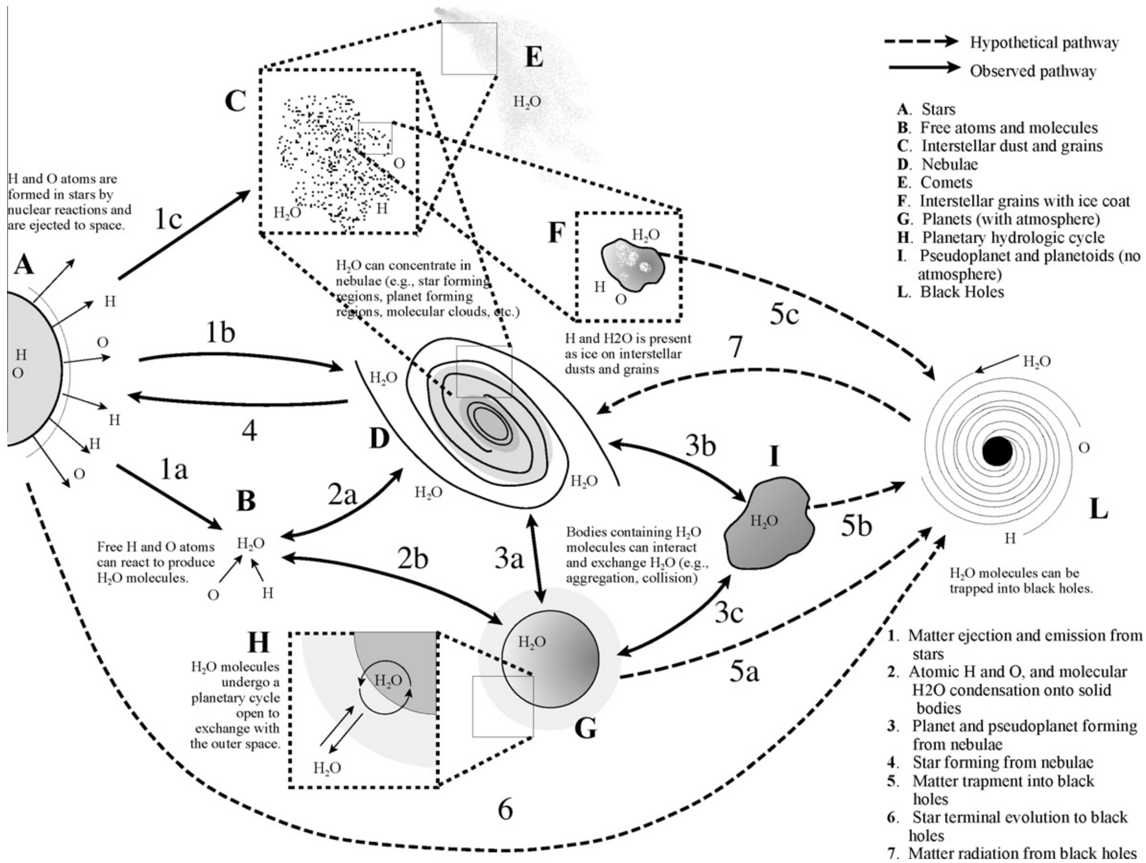

Fig. 1. A conceptual representation of the components of the hydrological cycle of water in the universe.

theoretical considerations suggest that a remnant nebula of matter may be left (Wallerstein et al., 1997), which would contribute to the interstellar matter. The processes described above, which are responsible for H and O emissions in the open space, are represented in Fig. 1 along pathways 1a, 1b and 1c.

In either emission scenario described above, H and O atoms do contribute to the interstellar medium (Fig. 1, icon C). This interstellar medium includes different phases (i.e., plasma, solid, gas) with differing density and temperature, some associated with stars and some not (Trimble, 1975). The mass of interstellar matter is found mainly in elements heavier than H, and the ratio of dust to gas mass in typical regions of the interstellar medium is about 0.01. A number of studies have reported on the distribution of H and O atoms in various planetary, stellar and interstellar regions and, in general, relative abundances of H and O at the scales of the open universe, solar system, and planets show similar values (e.g., Kotwicki, 1991). For example, abundances of H and O in interstellar clouds such as in the Magellanic Clouds (e.g., Aller et al., 1974) and the Sun (e.g., Ross and Aller, 1976) are relatively similar to the solar system abundance, while cosmic ray sources appear deficient in H and O from observations of Shapiro and Silberberg (1974) as reported in Trimble (1975).

After H and O are emitted in the interstellar space, they are not likely to react to form molecular water unless they condense from their plasma form at temperatures lower than about 182 K (Lodders, 2003). The view of the primary formation of H_2O molecules from condensed H and O atoms in the quiescent interstellar medium is still speculative, but it is not excluded that at lower temperatures than at the source, the relatively small fraction of H and (even lower) O gases in the interstellar medium can react to forms molecular H_2, O_2 and H_2O (Zmuidzinas et al., 1995; represented in Fig. 1, icon B). Hence, free water molecules may be present in the interstellar medium but is not clear if the origin of these H_2O molecules can be tracked back to isolated atoms reacting in the open space.

Recent studies have given a higher emphasis to primary formation of H_2O molecules through interactions with solids such as dusts and interstellar grains. During novae and supernovae events, massive quantities of energy and matter are ejected (Fig. 1, icon C and D). Condensed matter is suggested to form solid dusts and grains of various sizes (Fig. 1, icon F) made of graphite, silicates and iron (Hoyle and Wickramasinghe, 1970). Interstellar grains are also formed in regions with denser matter conditions such as in the atmosphere of cool stars and in circumstellar space, which are next ejected to interstellar space by the radiation pressure from the star (e.g., Aannestad and Purcell, 1973). The highest concentration of dusts and grains is found in nebulae such as molecular clouds, planet and star forming regions, and remnants of supernovae, but also in moderately dense clouds (Fig. 1, icon C, D and F). In molecular clouds, the density of matter can reach about 10^3 molecules per cm^3 but this can become 30 times higher in some regions (e.g., Cameron, 1988). Most reactions by which molecules are formed in interstellar space are suggested to occur on grain surfaces. In a moderately dense cloud (10^2 H molecules per cm^3), a grain will be hit by one H atom every few minutes. If all incident atoms were retained on the grain surface, a monolayer would accumulate in about 10^9 s ($\sim 10^2$ years, Aannestad and Purcell, 1973). Heavier O atoms would take longer time (in the range of 10^5–10^6 years) to result in a monolayer on grains. Thus, even if we exclude optimal adsorption conditions, interstellar grains would provide a means for accumulating and processing a substantial fraction of the interstellar H and O in a time short compared with the age of the universe ($\sim 10^{10}$ years, Ozer, 1999). Eventually, interception of H and O atoms at the grain surface, migration over the surface, and chemical reactions on the surface are the most likely mechanisms that produce water ice in the universe (Aannestad and Purcell, 1973; Gensheimer et al., 1996), and are represented in Fig. 1, icon C and F. Although no confirmation exists yet, one mechanism responsible for H_2O ice formation is suggested to be the reaction involving molecular H_2 as $H_2 + OH \rightarrow H_2O$. H_2 is suggested to be more abundant than atomic H (covering nearly 3% of grain surface) and is suggested to be produced from methane (CH_4) along the reaction $H + CH_4 \rightarrow CH_3 + H_2$ (Andersson et al., 2009). Molecular oxygen O_2 is proposed to be formed in the gas phase by the reaction $O + OH \rightarrow O_2 + H$. This O_2 would be next hydrogenated by atomic H to hydrogen peroxide (H_2O_2), which would lead to the production of water through the reaction $H + H_2O_2 \rightarrow H_2O + OH$ (Garrod and Pauly, 2011). Below 300 K, gas-phase water is likely produced by atomic O and H on the grain surface with subsequent sublimation (Brown et al., 1988), and this can explain the presence of free water ices, such as in the tail of comets (Fig. 1, icon E).

In general, water molecules are the most abundant molecules in clouds and are more abundant in hot-core than in cold-core molecular clouds (e.g., Brown et al., 1988). It has been also determined that water ice is the primary constituent of interstellar ices (Garrod and Pauly, 2011). These water molecules can move through the interstellar space by radiation and by transport on solid grains and dusts. These corpuscles are the matter that, when present in high concentrations in planet and star forming clouds, can aggregate in larger bodies including stars (Fig. 1, pathway 4, icon A and D), planets (Fig. 1, pathway 2 and 3, icon B, D and G), pseudoplanets, asteroids, etc. (Fig. 1, pathway 3, icon I and G). Interception and collision of grains and larger bodies such as planets and nebulae cause the exchange of water molecules and other matters. Not all interceptions and collisions have as an outcome the accretion of bodies (estimated to be efficient by less than 50% efficient, Agnor and Asphaug, 2004), but these types of interactions may be responsible for water exchanges and preferential accumulation of water molecules on one of the interacting bodies. Their overall effects on the astrohydrologic cycle are complex due to physical interaction between corpuscles and they imply mainly gravitational forces. These occurrences are represented in Fig. 1 by means of pathways 2, 3, and 4.

At the level of celestial bodies larger than dusts and grains, planets and pseudoplanets are the likely accumulation points of water molecules (Fig. 1, icon I and G). Upon acceptance that this water is temporary and not permanently resting on a planet, the turnover time of a water molecule can vary largely depending mainly on the gravitational attraction. If a planet is massive enough to hold an atmosphere, water molecules can be present in various phases, including as atmospheric water vapor. Under these circumstances, a water cycle like the one on Earth can develop. Yet, water vapor is not the necessary condition for a planetary hydrologic cycle as demonstrated by the evidences of the current hydrology on Mars. If an atmosphere is not present, water may be present most likely as ice such as on Mars and the Moon. Regardless of the presence of an atmosphere, water is only temporarily accumulated on these bodies. As discussed in the previous section, the reconstruction of the water cycle on Mars shows that water has been lost, mainly by radiation pressure from the solar wind on water molecules present in its atmosphere (Fig. 1, icon H). This type of mass exchange also exists on Earth and estimates suggest a water loss rate of about 7 m^3/s increasing up to about 50 m^3/s as the solar luminosity increases during its expected evolution (Kasting, 1989; Kotwicki, 1991). At the same time, Earth receives water from corpuscular radiation and from intercepted dusts, grains and meteorites. The amount of H and O atoms received from radiation fluxes can be estimated from the atomic composition of the solar wind, and can fall in the range $0.7\text{–}1.5 \times 10^{-3}$ m^3/s under the assumption that all H and O atoms react to form molecular water. It is presumed that a larger contribution of water transport to Earth could result from interstellar dusts, grains and meteorites. Although these fluxes are largely smaller than terrestrial net water fluxes ($\sim 7.7 \times 10^4$ m^3/s, e.g., Winter et al., 1998), they may affect the water budget at planetary time scales ($\sim 10^6\text{–}10^8$ years). These exchanges of water molecules are represented in Fig. 1, icon H.

Star forming regions in the universe are hypothesized to result from novae and supernovae. Woosley and Weaver (1995) described the explosion and evolution of stars in the range 11–40 times the mass of the Sun and suggested that supernovae may be followed by a second collapse of remnant matter and by white dwarf stars, neutron stars, or black holes as the possible outcome (Wallerstein et al., 1997; Joshi, 2011). Newly-generated stars would recycle the matter in the universe including free H and O atoms in the space, the water ice accreted on interstellar dusts and grains, and the water molecules on larger bodies (Fig. 1, process 4). These new-generation stars would be again a source of H and O atoms according to the emission processes described before. One pathway in the possible evolution of stars after supernovae events could be the formation of black holes (Fig. 1, pathway 6, icon L). In the widely accepted context, black holes would attract matter including all celestial bodies mentioned above without releasing them (Fig. 1, pathways 5a, 5b and 5c). The existence of black holes is not substantiated yet but it is hypothesized that a big black hole resides at the center of the Milky Way and possibly of all galaxies in the universe (Fryer and Heger, 2011). Whereas black holes are conceived as being terminal attractors of all matter, they are hypothesized, under some circumstances, to release back energy in the form of radiation and therefore matter (e.g., Hawking, 1975) as in Fig. 1, pathway 7. This pathway would suggest that a further pathway to matter and water recycling may be present in addition to the one described before.

In summary, an astronomical cycle of water is proposed here to occur along various pathways starting with the synthesis of H (mainly in the Big Bang) and O plasmas in stars, which are ejected in space by radiative flows and by supernovae explosions. Condensation of H and O to atomic forms, and formation of water ice would mainly occur at the surface on solid interstellar dusts. In some regions of space, a high density of interstellar corpuscles such as in molecular clouds and nebulae can evolve to result in larger bodies, such as planets. Accumulation of water on solid, large celestial bodies may result in local planetary hydrologic cycles. The astrohydrologic cycle closes when clouds and nebulae including bodies larger than dusts collapse to form new-generation stars.

5. Benefits of developing astrohydrology

Understanding the behavior of water in space and on other planets could benefit manned space exploration and planetary exploration, and permanently-inhabited extraterrestrial outposts (e.g., ESA-Mars 500; ISECG, 2007). In this context, recent studies have investigated, for example, if water could be a means to support bioregenerative agriculture for small crews (e.g., Silverstone et al., 2003; Maggi and Pallud, 2010a,b) and if water could be extracted from Mars' superficial regolith using microwaves to melt and vaporize ice crystals during manned missions (Wiens et al., 2001). However, uncertainties are still very high with respect to the proposed techniques and, above all, with respect to the exact behavior and interactions that water could have with the solid matrix of Mars.

Because water dominates environments at the surface of the Earth and is tightly connected to life, finding water on other planets is often perceived as the ultimate step to the discovery of past or present extraterrestrial life (Ball, 2005). For example, the Jupiter's moons Europa, Ganymede and Callisto have features linked to water-dissolved salts and geothermal processes that fuel speculations toward their habitability by primordial forms of life (e.g., Gaidos et al., 1999; Chyba and Hand, 2005), while hypotheses of the habitable zone in planets of other solar systems have been proposed as well (e.g., for the star Gliese 581, Selsis et al., 2007). On a different level of speculation is the hypothesis investigated by McKay et al. (1991) to make Mars habitable. Within their analyzes, water and CO_2 would play a key role to strengthen the greenhouse effect and increase the surface temperature to make the atmosphere suitable to host liquid water and plants. Whereas habitability and human colonization of other planets are still far from being feasible and motivated by water alone, reasoning about water off Earth helps addressing our attention to water on a larger scale, in the entire universe, and not limitedly to Earth only.

All these examples show that the principles of terrestrial hydrology may point to new important to new hypotheses and provide explanations on how hydrological processes on Mars and Venus could have evolved, or how unique surface features such as on Europa could have been produced by belowground water movement. Yet, these theories do not lead to tangible conclusions. The principles of Earth's hydrology may apply to astrohydrology only under limited circumstances and cannot yet fully explain the complex phenomenology of waters in the universe. The gap in our knowledge of the macroscopic parameters that drive hydrological processes in exotic gravities, temperatures, pressures, and astrophysical conditions commonly encountered on other systems still needs to be filled. Hydrologists are the scientific figures to be made aware of the great challenges that are rising in this discipline, and the ones who can carry astrohydrology through from its infancy to its maturity.

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