The water trail from the cradle of a young Sun to Earth-like planets

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Abstract / Resumen / Résumé

Water is a crucial ingredient for the emergence of life. Therefore one of the most intriguing issues in the field of Astro-biology and Astro-chemistry is to understand the origin of water on Earth. We know that our oceans contain an amount of water of about 3 tenths of a thousandth of the total Earth mass. However, if we consider also the water below the Earth crust the total amount of water could be up to 10-50 times more. There are many open questions about our precious reservoir of water, for example: When and how did water arrive on Earth? Is our planet a special case or is there water, and possibly life, also in extra-solar planets orbiting other stars in our Galaxy? With more than 1000 exoplanets discovered to date and statistics indicating that every star hosts at least one planet, the search for water in the universe is more and more urgent.

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El agua es un ingrediente crucial para la vida. Una de las áreas de investigación más fascinantes en el campo de la astrobiología y la astroquímica es la del origen del agua sobre la Tierra. Sabemos que nuestros océanos contienen una cantidad de agua igual a 3 diezmilésimas de la masa terrestre. Sin embargo, si consideramos también el agua presente bajo la costra terrestre, el total podría aumentar a entre 10 y 50 veces más. Existen muchas cuestiones por resolver, como por ejemplo: ¿Cuándo y cómo apareció el agua sobre la Tierra? ¿Nuestro planeta es un caso especial o hay agua, y posiblemente vida, en otros planetas de nuestra Galaxia? Con más de 1000 exoplanetas descubiertos y las estadísticas que indican que cada estrella alberga al menos un planeta, la búsqueda de agua en el universo es cada vez más urgente.

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L'eau est un ingrédient crucial pour la vie. L'un des domaines de recherche plus fascinants de l'astrobiologie et l'astrochimie est celui de l'origine d'eau sur Terre. Nous savons que nos océans contiennent une quantité d'eau égale à 3/10000 de la masse terrestre. Cependant, en tenant compte également de l'eau présente sous la croûte terrestre, le total peut augmenter entre 10 et 50 fois plus. Il y a nombreuses questions en suspens, telles que: Quand et comment l'eau est apparue sur Terre? Est notre planète un cas particulier, ou est-ce que l'eau, et peut-être la vie, existent sur d'autres planètes dans notre galaxie? Avec plus de 1000 exoplanètes découvertes et les statistiques indiquant que chaque étoile abrite au moins une planète, la recherche de l'eau dans l'univers devient de plus en plus urgente.

Key Words / Palabras clave / Mots-clé

Star and planet formation, water, space telescopes

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Formación estelar y planetaria, agua, telescopios espaciales

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Formation stellaire et planétaire, eau, télescopes spatiaux

1. The Star and Planet Formation Process

To address the origin of water on Earth it is essential to understand the process that about 4.5 billion years ago brought to the formation of the Sun and the Solar System. As we cannot go back in time and look at the Sun and the planets as they were in the past, we observe young Sun-like stars in our Galaxy which are at different stages of the long (about a few million years) and complicated process of the formation of a star. Our current picture of the star and planet formation is schematically illustrated in Figure 1.

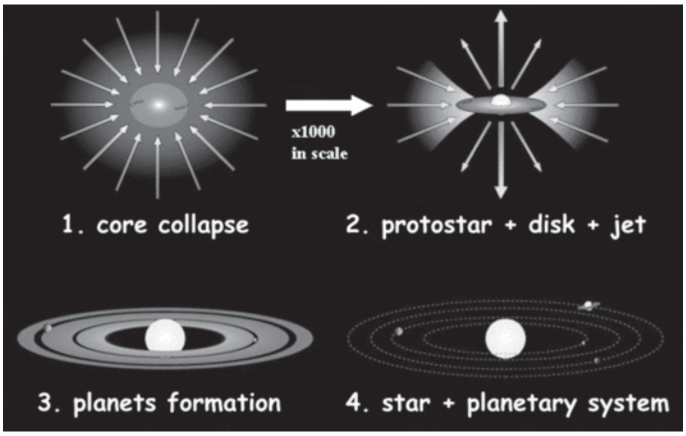

Figure 1: *The star formation process (adapted from McCaughream)*

Sun-like stars form from the gravitational collapse of dense and cold regions of gas and dust inside molecular clouds, called prestellar cores (Stage 1). The collapse produces a disc rotating around the central forming star, known as protostar, which accretes material from it thus increasing its mass. At the same time, the protostar also violently ejects mass in the form of supersonic bipolar jets, which transport the excess energy and angular momentum away from the central object. The jets also sweep out the surrounding cloud material creating large and slow outflows (Stage 2). The material of the parental cloud is gradually dispersed by the jet and accreted onto the star, until it reaches its final mass. Simultaneously, the micron sized dust grains in the disc coagulate and grow into larger and larger bodies, thus forming planetesimals, i.e. rocks larger than 1 km, which are the building blocks of planets, asteroids, and comets. These newly born planets excavate holes in the disc (Stage 3). The star formation process is concluded when the star starts burning hydrogen in its interior, like our Sun. At this stage the star may possibly be surrounded by a planetary system like our own (Stage 4). The study of the physics and chemistry of gas and dust across the different stages of the star formation process, i.e. in prestellar cores, protostars, outflows, and discs, and of their water content, is fundamental to comprehend the emergency of life in our own solar system as well as in extrasolar planetary systems.

2. The search for water: 15 years of space missions

Water may be present in star-forming regions either as gas or as ice on the surface of dust particles, depending on the physical and chemical conditions of the environment. Water vapour has an extremely rich spectrum from the sub-millimetre to the near-infrared wavelength range. Unfortunately, the detection of these lines from Earth is completely blocked by the water vapour in the atmosphere, even at the high altitudes reached by aircraft and balloons. To overcome this problem, in the last 15 years there have been several space missions (see Figure 2):

1. the *Infrared Space Observatory (ISO)*, designed and operated by the European Space Agency (ESA), in cooperation with ISAS (part of JAXA as of 2003) and NASA, was launched on 17 November 1995 and operated until 1998, allowing to observe between 2.5 and 240 μm.
2. the *Submillimetre Wave Astronomy Satellite (SWAS)*, launched on 5 December 1998 as part of the Small Explorer program within NASA, to observe from 540 to 610 μm. It was operative until July 2004.
3. the *Spitzer Space Telescope (SST)*, the fourth and final of the NASA Great Observatories program, was launched on 25 August 2003 and observed the universe between 3 and 180 μm until May 2009.
4. and, finally, the *Herschel Space Observatory*, an ESA mission, launched on 14 May 2009 and active until 2013, allowed to observe between 55 and 670 μm.

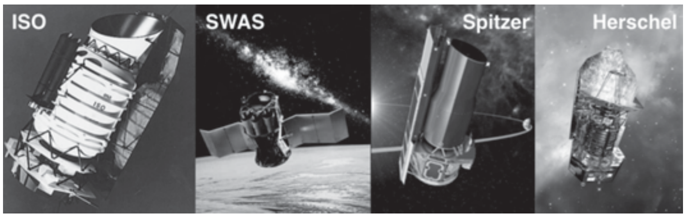

Figure 2: *Space missions to observe water in space*

These missions have shown that water is ubiquitous in our universe and is present at all stages of the star-formation process from cold molecular clouds where stars form to young stars of a few to 100 thousand years old. In the last 5 years Herschel has revolutionised the field allowing to detect water vapour in a cold and dense prestellar core where a sun-like star is about to form (see Section 3), in jets and outflows driven by young protostars (Section 4), and even in the discs around stars of a few million years which could possibly form a system of planets like our own solar system (see Section 6). Last but not least, Herschel has allowed to derive the properties of water in a comet in our solar system, a fundamental piece of information to understand how the water contained in our pristine solar nebula was delivered to Earth (Section 7).

3. The first detection of water vapour in the cradle of a Sun-like star

As explained in Section 1, molecular clouds are nurseries of young stars. These clouds are very cold (with temperatures of around 10 to 30 K, where 0 K corresponds to -273.15 ˚C), thus almost all the water is located in the icy coats of the dust grains. This makes the detection of water at those early stages very difficult.

Recently, Herschel observations of a cold and dense prestellar core in the constellation of Taurus known as Lynds 1544 allowed to detect, for the first time, water vapour in a molecular cloud on the verge of star formation (see Figure 3). This discovery was possible thanks to a large team of European and extra-European researchers led by Prof. Paola Caselli, director of the Max Planck Institute for Extraterrestrial Physics (Garching, Germany), in the context of the Herschel project WISH (Water In Star-forming regions with Herschel). The results are published in Caselli et al.

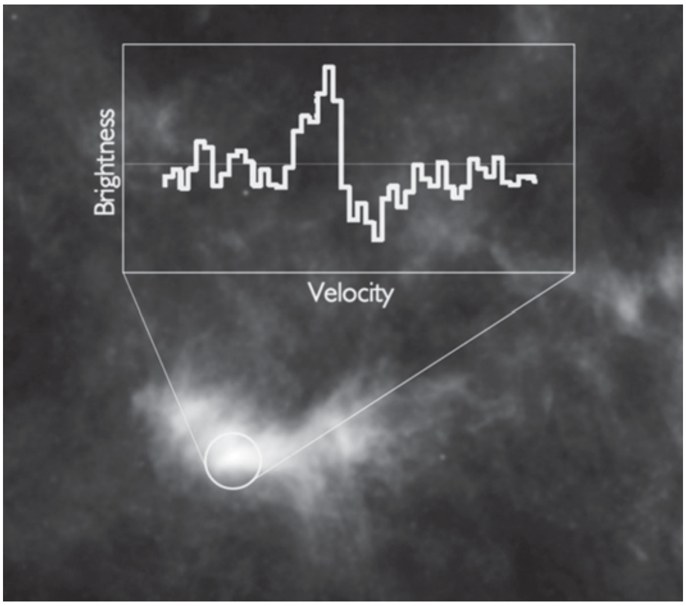

Figure 3: *Herschel detection of water vapour in the prestellar core L1544. The profile of the water line shows an excess in brightness (emission) and a deficit (absorption). This indicates that the emitting water molecules are moving toward the centre of the core, which means that the cloud is undergoing gravitational contraction to form a new star (from Caselli et al. 2012: ApJ, 759, L37). Copyright: ESA/Herschel/SPIRE/HIFI/Caselli et al.* (2012: ApJ, 759, L37).

The detected water vapour amounts to more than 2000 Earth oceans, liberated from icy dust grains by high-energy cosmic rays passing through the cloud. Theoretical models show that to produce that amount of vapour, there must be a lot of water ice in the cloud, more than three million frozen Earth oceans' worth. Moreover, the velocity profile of the detected water line revealed that the water molecules are flowing towards the heart of the cloud indicating that gravitational collapse has just started. This means that even if there are no stars in this dark cloud today, a new star is probably about to form. The material in the core is enough to form a star at least as massive as our Sun. Some of the water vapour detected in L1544 will go into forming the star, but the rest will be incorporated into the surrounding disc, providing a rich water reservoir to feed potential new planets.

4. Water in jets and outflows by young Sun-like stars

As illustrated in Figure 1, once the prestellar core becomes gravitationally unstable the collapse starts. The radiation energy released by the accretion of matter onto the newly born protostar is absorbed by the dense surrounding cloud, which quickly heats up. At the same time, the supersonic bipolar jets driven by the nascent star encounter the dense ambient medium, producing strong shock waves that increase the gas temperature up to a few thousand kelvin. In such warm environments, two processes are expected to produce water very efficiently. As the temperature of the dust grains rises above about 90 K, their ice coats release water by evaporation. Moreover, at gas temperatures above about 300 K, all the available atomic oxygen is rapidly transformed into water. Under these conditions, the water amount is expected to increase spectacularly with respect to cold clouds.

These expectations were confirmed by Herschel observations, which revealed abundant water in jets and outflows (see for example Codella et al. 2010: A&A, 522, L1 and Nisini et al. 2010: A&A, 518, L120). A wonderful example is represented by the L1157 outflow powered by the Sun-like protostar L1157-mm, which displays two lobes expanding away from the central protostar toward opposite directions (see Figure 4). L1157 is the prototype of the so-called "chemically active" outflows, and is therefore an excellent laboratory to investigate the formation of H_2O in shocks. For this reason it has been studied in the framework of two Herschel projects: WISH (see Section 3) and CHESS (Chemical HErschel Surveys of Star forming regions). Figure 4 shows the emission in molecular hydrogen observed by Spitzer (left panel) and the new map in the water line at 179 micron obtained with Herschel (right panel). The latter shows that the water emission peaks where the jet interacts with the cloud creating shocks (in yellow and magenta) and close to the protostar where the gas is heated by stellar radiation.

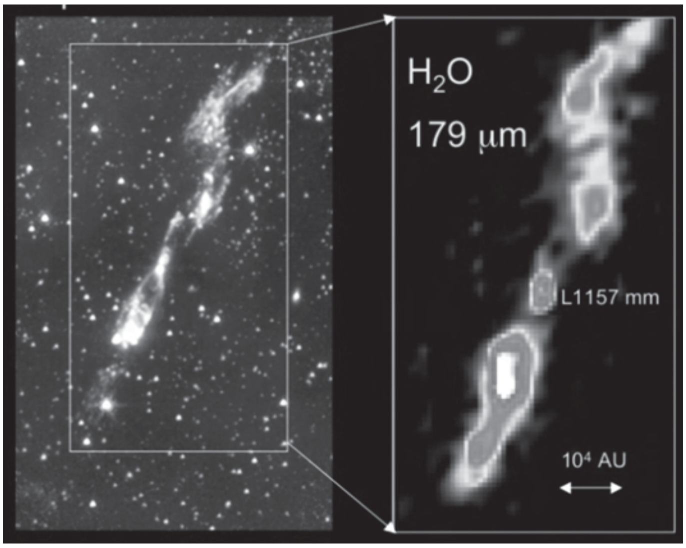

Figure 4: *The L1157 bipolar outflow, driven by the L1157-mm protostar, as seen by Spitzer in molecular hydrogen emission (Left) and by Herschel through water emission at 179 micron (Right). The outflow shows two lobes, one approaching (south) and one receding (north) with respect to us. Figures from Looney et al. (2003: ApJ, 670, L131) and Nisini et al. (2010: A&A, 518, L120).*

5. Water in meteorites and theories for the origin of water on Earth

As shown in Figure 1, discs are the birthplaces of planets. Hence, the formation of planets depends sensitively on the physical conditions of the gas and dust in the young protoplanetary disc. The chemical composition of the planetesimals from which planets, asteroids and comets are built-up determines their volatile and liquid chemical composition.

A method to infer the composition of the planetesimals from which the Earth formed consists of looking at asteroids, i.e. the left overs of the disc that once was around our Sun. Asteroids can be easily studied through meteorites, solid rocks from the asteroids belt that cross the Earth's atmosphere and survive impact with the Earth's surface. Meteorites show a gross correlation between their H_2O content and their original distance from the Sun; in particular, meteorites from the inner asteroid belt, located at around 2 astronomical units (AU) from the Sun, are quite dry, with an amount of water which is less than one thousandth of their total mass. This suggests that the Earth, which is located at 1 AU from the Sun, formed from even dryer planetesimals. According to disc models this is due to the fact that the dust grains in the inner region of the disc are heated by the star, therefore their ice coat is completely evaporated. Beyond the so called snow-line (which is located at about 2-3 AU in Sun-like stars), instead, water molecules are frozen onto dust grains, that will coagulate and grow forming icy planetesimals, which could then form icy asteroids, comets, and planets.

Based on these evidence it was argued that Earth formed as a dry planet and ocean water was delivered to Earth by icy bodies, such as asteroids and comets, originating from the cold outer disc, where most of the water ice is located (Matsui & Abe 1986: Nature, 322, 526). These asteroids and comets could have impacted the Earth leaving their water treasure about 3.5 billion years ago during the so-called late bombardment phase.

6. The first detection of water in protoplanetary discs

To verify the idea that the Earth formed dry and that water was delivered on it at a later stage by "icebergs" forming in the outer regions of the solar system, several efforts have been devoted to observing water in protoplanetary discs and to characterising its abundance and spatial distribution. While the hot water vapour located in the inner disc region was observed with the Spitzer space telescope in a number of discs (see, e.g., Carr & Najita 2008: Science, 319, 1504), the cold water reservoir in the outer disc remained hidden as most of it is frozen onto the dust grains.

Recently, the Herschel space observatory has found evidence of water vapour released from ice on grains in the discs around the young stars TW Hya and DG Tau. Those stars are about 2 to 10 million years old and are only 176

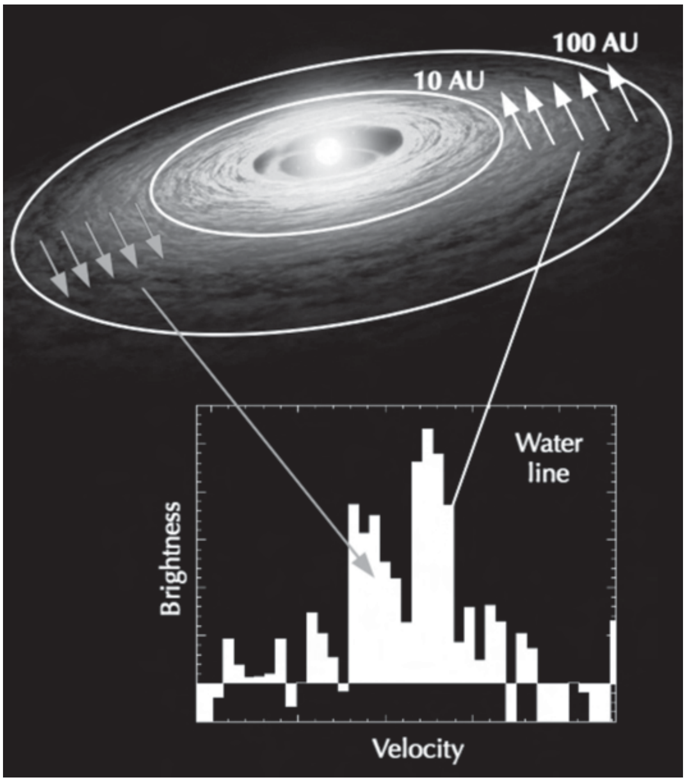

Figure 5: *Herschel detection of water vapour in the protoplanetary disc of DG Tau. The profile of the water line shows two peaks which trace the borders of the disc, one approaching (blue) and one receding (red) with respect to the observer (from Podio et al. 2013: 766, L5). Credits: NASA/JPL-Caltech/T. Pyle, ESA/Hershel/HIFI*

and 450 light-years away. The discovery of cold water vapour in those discs has been obtained by two international teams: the first one led by Michel Hogerheijde of Leiden University in the Netherlands, in the context of the Herschel project WISH (see Section 3); and the second one led by Linda Podio of INAF-Arcetri Astrophysical Observatory, Florence, Italy, and in the context of the Herschel project GASPS (GAS in Protoplanetary Systems). The results are published in Hogerheijde et al. (2011: Science, 334, 338) and Podio et al. (2013: ApJL, 766, L5). The observed water vapour is only a tiny percentage of the total water trapped onto dust grains, and is released from their mantles due to interstellar cosmic rays. The water lines imply a hidden ice reservoir of a few to 100 thousand Earth oceans. This could be a rich source of water for any planets that will form in the disc around these young stars. This research breaks new ground in understanding water's role in planet-forming discs and gives scientists a new testing ground for looking at how water came to our own planet.

7. Water in comets: new clues on the origin of Earth oceans

Another important step into the comprehension of the origin of water on Earth has been made thanks to Herschel observations of water in the comet Hartley 2, which shows almost exactly the same composition as Earth's oceans. As explained in the ESA-Herschel press release, this discovery supports the idea that comets, which are basically giant rocks covered by ice, delivered water on Earth by colliding on it.

Comets travel through space with orbits that take them across the paths of the planets, making collisions possible. Moreover, in the early Solar System there were larger numbers of comets, therefore collisions would have been much more common. The key measurement to back up this idea is to measure the level of deuterium –a heavier form of hydrogen– found in water. All the deuterium and hydrogen in the Universe was made just after the Big Bang, about 13.7 billion years ago, fixing the overall ratio between the two kinds of atoms. However, the ratio seen in water can vary from location to location. The chemical reactions involved in making ice in space lead to a higher or lower chance of a deuterium atom replacing one of the two hydrogen atoms in a water molecule, depending on the particular environmental conditions. Thus, by comparing the deuterium to hydrogen ratio found in the water in Earth's oceans with that in extraterrestrial objects, astronomers can aim to identify the origin of our water.

All comets previously studied had shown deuterium levels around twice that of Earth's oceans. If comets of this kind had collided with Earth, they could not have contributed more than a few percent of Earth's water. Indeed, astronomers had begun to think that meteorites must have been responsible, even though their water content is much lower.

Now, however, Herschel has studied comet Hartley 2 using HIFI, the most sensitive instrument so far for detecting water in space, and has shown that at least this one comet does have ocean-like water (see Figure 6). This important discovery has been carried out by an international team of astronomers led by Paul Hartogh, from Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany, and published on Nature (Hartogh et al. 2012: Nature, 478, 218).

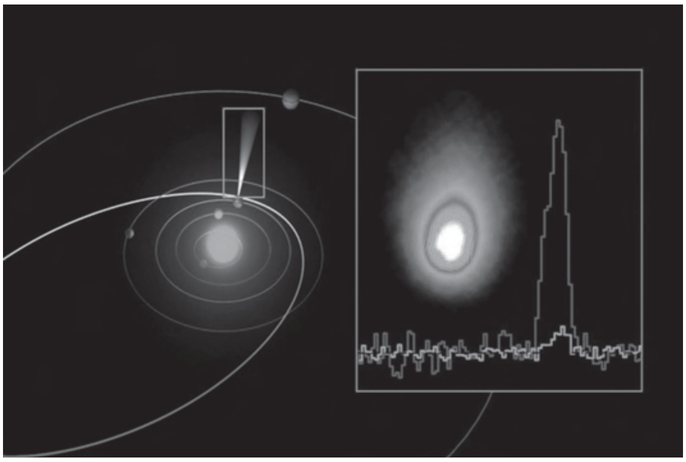

Figure 6:*This illustration shows the orbit of comet Hartley 2 in relation to those of the five innermost planets of the Solar System. The comet made its latest close pass of Earth on 20 October 2010, coming to 19.45 million km. On this occasion, Herschel observed the comet. The inset on the right side shows the water lines obtained with Herschel.*
Figure adapted from Hartogh et al. (2012: Nature, 478, 218).
Credits: ESA/AOES Medialab; Herschel/HssO Consortium

More evidence supporting the role of comets in delivering water to planets arrived from Herschel observations of Jupiter. These have shown that the water in its upper atmosphere was delivered by the dramatic impact of comet Shoemaker-Levy 9 in July 1994.

The 1994 impact lasted one week and was observed worldwide by amateur and professional astronomers, being the first direct observation of an extraterrestrial collision in the Solar System. During the collision, comet fragments pounded into the southern hemisphere of Jupiter, leaving dark scars in the planet's atmosphere that persisted for several weeks. Since the first detection of water in Jupiter's upper atmosphere, obtained thanks to the ISO telescope in 1995, it was suggested that the observed water could have been released by comet Shoemaker-Levy 9, but direct proof was missing. Herschel observations found that there was 2–3 times more water in the southern hemisphere of Jupiter than in the northern hemisphere, with most of it concentrated around the sites of the 1994 comet impact, definitively confirming that the observed water was delivered during the impact. This remarkable discovery was published by an international team led by Thibault Cavalié of the Laboratoire d'Astrophysique de Bordeaux, France (Cavalié, T. et al. 2013: A&A, 553, A21).

8. The future: new instrumentation to investigate the origin of water

As illustrated in this chapter, the Herschel space observatory, designed and operated by the European Space Agency, was key to carry out our search for water in the universe and to understand the origin of life. Unfortunately Herschel stopped observing since 29 April 2013, when it ran out of liquid Helium. This was used to keep the instruments at a temperature of about -271 ˚C, which is crucial to make them sensitive to the faint emission from young stars. Therefore, at the moment there are no space telescopes to observe in the far-infrared range where the water lines emitted from cold to warm protostellar regions can be observed.

To fill in the void left by Herschel, astronomers and engineers are working to produce new instrumentation to explore the universe at far-infrared wavelengths, such as the SPICA telescope or even an array of space telescopes which should work simultaneously to produce far-infrared images at unprecedented resolution (see the FISICA project funded by the EU under the seventh framework programme FP7). Alternatively, we can search for water using the Atacama Large Millimetre Array (ALMA), an array of more than 60 antennas that combines the collected light to increase the sensitivity and resolution of the observations. The ALMA scientists and engineers are now projecting a new detector to observe around 1.5 millimetres where we should be able to detect the faint emission from the heavy water isotopologue $H_2^{18}O$.

Hopefully the new instrumentation will give us new clues about the origin of water on Earth and will allow us to investigate the possibility of alien life in our universe.

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