ISO was the world's first true orbiting infrared observatory, providing astronomers with unprecedented sensitivity and capabilities at infrared wavelengths from 2 to 240 microns. Launched in November 1995 and operational until April 1998 – almost a year longer than specified – ISO was also a great technical and operational success. Its 60cm-diameter telescope was cooled by superfluid liquid helium to temperatures of 2 to 4K. ISO was equipped with four highly-sophisticated and versatile scientific instruments, two spectrometers, a camera and an imaging photopolarimeter, all built by laboratories and institutes in ESA Member States (especially the Principal Investigator countries: France, Germany, The Netherlands and the United Kingdom). ISAS and NASA participated in the project. Some 30000 individual imaging, photometric, spectroscopic and polarimetric observations were made of all classes of astronomical objects and these data are now available to all. ISO's scientific results are impacting all areas of astronomy, literally, from comets to cosmology.

ISO* and Cosmic Water

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Water, the basic substance essential for life, has been detected by the Infrared Space Observatory (ISO) in many places throughout the Universe, including our planetary neighbours in the Solar System, clouds circling or pouring out of stars, the vast spaces between stars, and distant galaxies. We show here how these observations enable us to reconstruct the cosmic cycling of water, and its relevance to the presence of water on the Earth.

How can water be detected?

The water molecule consists of two atoms of hydrogen and one atom of oxygen, linked together in an unusual asymmetric way, with a bond angle between the two hydrogen atoms of 105 deg, rather than a symmetric 180 deg (Fig. 1). This geometry is responsible for many of its special properties, including making it a universal solvent. Like any other molecule, the atoms vibrate and rotate, but nature allows only a finite number of possibilities for the energy states of the molecule, governed by the laws of quantum mechanics. Thanks to the peculiar geometry, water can be found in many different rotational-vibrational states, and it is possible to observe a molecule changing from one of these states to another by detecting the radiation that accompanies each transition. The relative population of these energy levels depends on physical parameters such as density and temperature. The change between states is associated with an absorption (if going to higher energy levels) or emission of radiation, at specific wavelengths in the infrared or submillimetre part of the spectrum. The infrared radiation carrying the information on the physics of water in the Universe is, however, lost when it has to transit Earth's humid atmosphere after having travelled through space for millions of years. Our atmosphere is highly opaque throughout the whole infrared region of the spectrum.

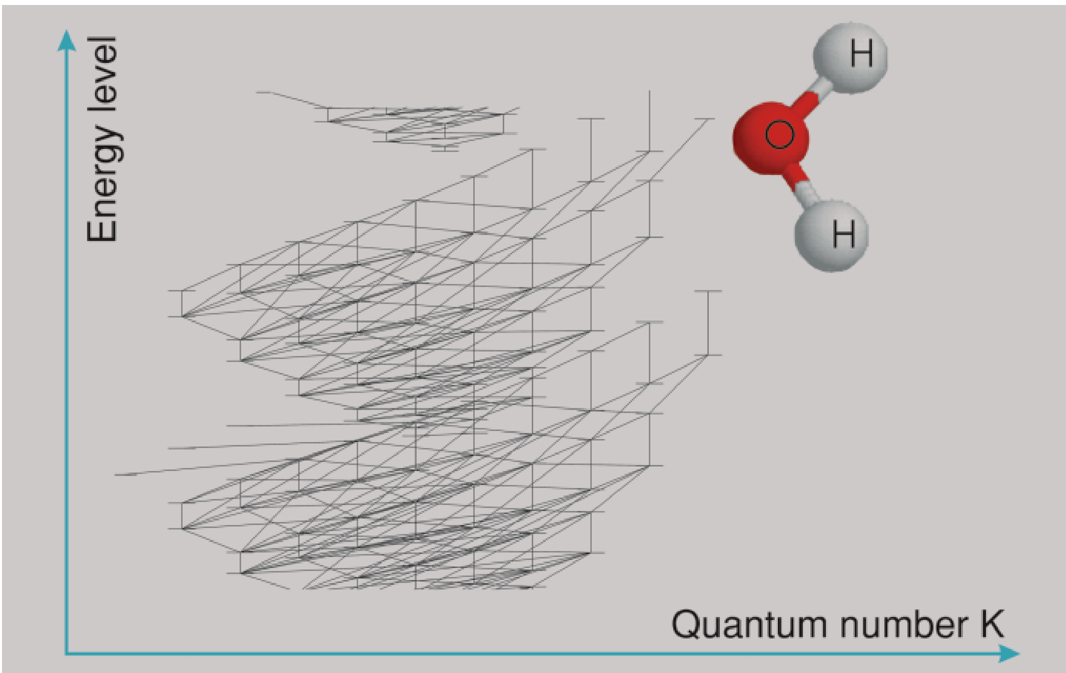


Figure 1. Energy-level diagrams for vibrational/rotational levels of the water molecule. Each level is characterised by an integer value of several quantum numbers, one of which is designated K. The transitions shown here occur in the wavelength range covered by ISO, corresponding to gas temperatures ranging from 1000 to 6000 K. Such a wealth of transitions is due to the non-linear shape of the molecule, while its symmetry causes the transitions to be divided into the two classes – those with even K are called para- while odd K are called ortho- (for simplicity, only the latter set is shown here). ISO observations have shown that the ratio of the ortho- to the para- form of the molecule in many objects is less than the equilibrium value of 3 (Adapted from K. Volk)

* Additional information on ISO, including results galleries and how to retrieve data, can be found by following links from the ISO Home Page (www.iso.vilspa.esa.es); news items are also posted at www.sci.esa.int. Previous ESA Bulletin articles have addressed: the scientific results (Kessler et al., No. 99, September 1999); the data archive (Arviset & Prusti, No. 98, June 1999); the ISO operations (Kessler, Clavel & Faelker, No. 95, August 1998); early ISO results (Kessler, No. 86, May 1996); and pre-launch descriptions of the overall mission (No. 84, November 1995).

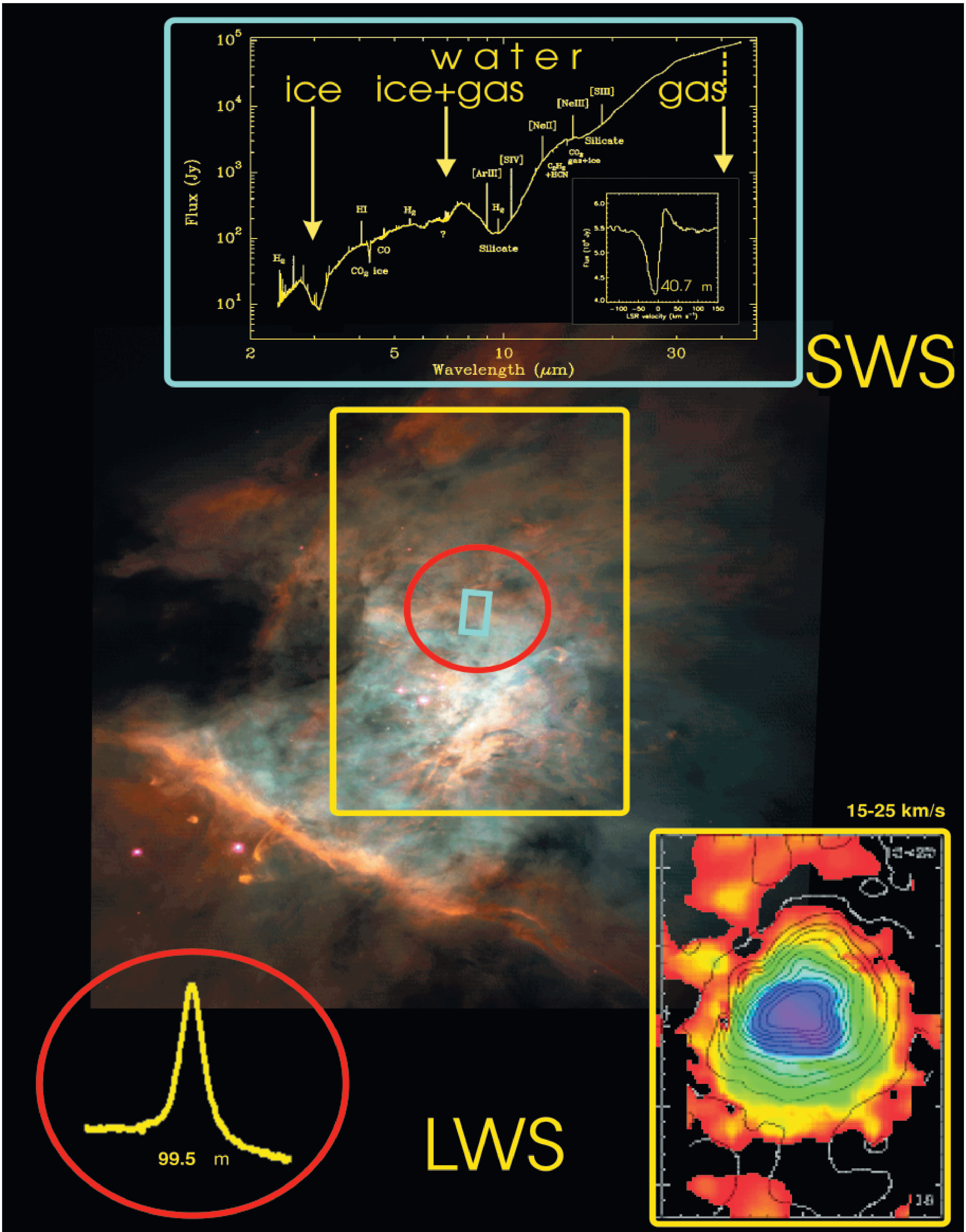


Figure 2. Water detection in the Orion nebula. The area covered by the SWS spectrometer (shown in blue) presents a wealth of atomic, ionic and molecular lines seen in Orion IRC2, superimposed on a thermal emission from warm (50 - 300 K) dust. Water lines were also detected by the LWS spectrometer (in red). The water lines are detected in emission and in absorption, indicating a complex geometry. A mapping performed with the LWS (in yellow) shows that water is present over a large area, at velocities of the order of 70 000 km/h (Credits: SWS / E. van Dishoeck, C. Wright et al.; LWS / M. Harwit, J. Cernicharo et al.; NASA/HST / C.R. O'Dell, S.K. Wong)

Some information on water in space has been retrieved from peculiar, isolated lines in the radio range, so-called ‘maser lines’, which occur in very small, cool regions, often close to a young star that is still being formed, but the interpretation of these lines is difficult.

ISO was the first true infrared observatory in space and provided astronomers with the direct, simultaneous detection of tens to hundreds of spectral lines of water, thereby allowing the physical conditions – the temperature, density, chemical composition – and in some cases also the dynamics of the emitting regions to be determined. Thanks to ISO’s spectrometers, astronomers now know more securely how much water there is in these regions. In some cases water is present on very large scales.

How is water formed?
The ingredients needed to form water are readily available in the Universe, hydrogen being the most abundant element. It has existed since the ‘big-bang’, which marked the formation of the known Universe some 12-15 billion years ago. Stars, like our Sun, produce heavier elements by nuclear reactions ‘burning’ hydrogen in their centre. Oxygen is created in the centre of massive stars and released into space via stellar winds or supernova explosions. Heavy elements wander in space – in the colder regions, some stick together, forming grains. Interstellar dust grains are either silicate (coming from oxygen-rich stars) or carbonaceous grains (from carbon-rich stars) and are typically 0.1 microns (one ten-thousandth of a millimetre) in size. It appears from infrared measurements of distant galaxies that star formation was more frequent in the early epochs of the Universe, when it was only a billion years old.

The space between stars, known as the ‘Interstellar Medium’, thus contains the ingredients for water in large quantities. In order for these ingredients to actually form water, a temperature of a couple of hundred degrees above the absolute level (0 Kelvin) is required to trigger chemical reactions. The Interstellar Medium is generally cold (about 10 Kelvin), but in certain places its temperature can reach thousands of degrees, such as in the violent processes associated with the formation of stars.

Therefore, ISO was expected to find water, with an abundance of at least 1 part in 10 million hydrogen molecules (10^{-7}), and it was inferred from the above-mentioned maser lines that water could reach an abundance of one molecule per 10 000 hydrogen molecules (10^{-4}) in star-formation regions. Water was predicted to be the dominant oxygen-bearing species in warm (~1000 K) dense gas (other oxygen atoms would stick to carbon). ISO not only fulfilled its promise, but also provided previously unexpected detections of water, allowing more links to be established between the distant Universe and ourselves.

Let us now embark on a hypothetical journey through the cosmic cycle of water, as revealed by a few examples extracted from the total database of some 30 000 observations made by ISO.

Orion: a cosmic factory
The richness of the infrared spectrum, opened up by ISO’s spectrometers, can be seen in the spectrum of Orion (Fig. 2). This nearby nebula (‘only’ 1500 light years from us) is one of the most studied molecular clouds and star-forming regions because of its brightness and proximity. A wealth of atomic and molecular lines, among them water, are visible, superimposed onto a continuum originating from the emission of warm dust (at 50 – 300 K). Large quantities of water are produced when the gas and dust undergo gravitational collapse, as part of the process leading to the formation of a star. The temperature increase in the centre of the contraction drives violent supersonic waves, travelling at more than 60 000 km/h, which increase the temperature in the outer regions, triggering the transformation of hydrogen and oxygen into water. The newly-formed water releases part of the energy via the above-mentioned rotational-vibrational transitions, and thus prevents the gas from expanding again. It was indeed expected that water would be a major ‘coolant’, thus promoting the collapse of clouds of gas and dust to form a star.

It has been calculated from the ISO observations that Orion is producing enough water to fill the Earth’s oceans 60 times a day. Almost one hundred water lines have been detected in the central region of Orion – some in emission and some in absorption – indicative of a turbulent geometry of gas and dust. The map shown in Figure 2 led to the determination of the water distribution over a region as wide as 100 000 times the Earth-Sun distance (one Astronomical Unit, AU). The derived abundance in Orion of 10 molecules of water per million hydrogen molecules in the so-called ‘ridge’, increasing to 500 molecules in the centre confirmed the expectations.

Another example of the production of water over a wide, extended region is provided by Sgr B2, a huge molecular cloud located close to

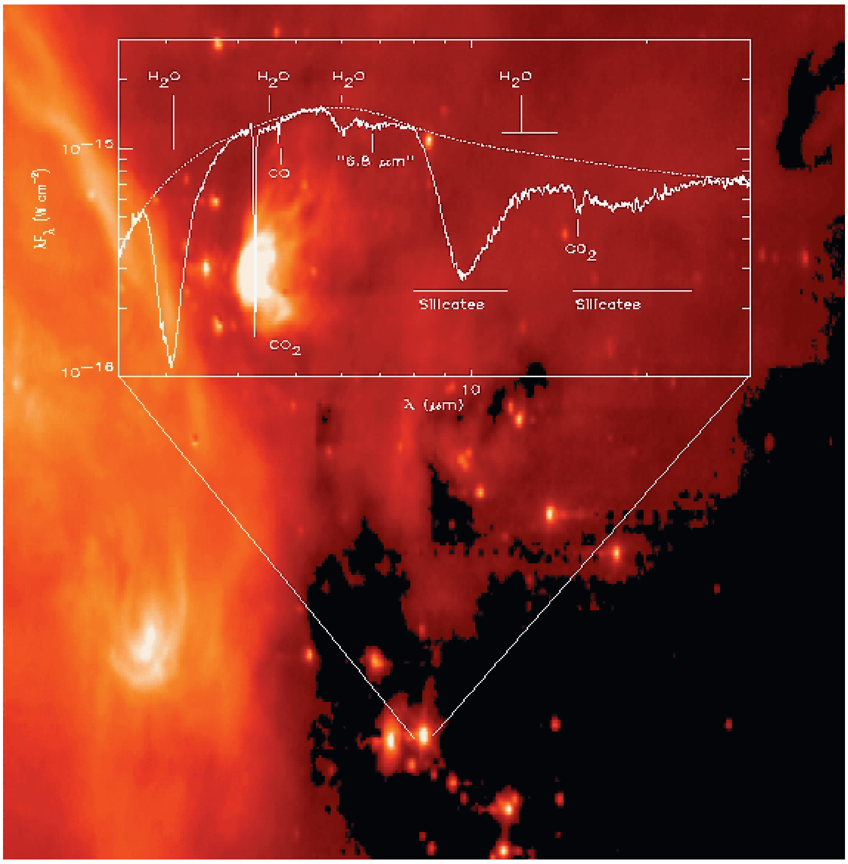


Figure 3. The low-mass protostar Elias 29 is located in the dense molecular cloud Rho Ophiuchi. It is one of the two bright IR spots in the centre of this composite image obtained with the ISOCAM using 6 and 16 micron filters. The absorption spectrum of the interstellar material is dominated by the water-ice bands at 3 and 6 micron due, respectively, to the ice molecule O-H bond variation with inter-atomic distance (stretching mode) and the varying angle between the two hydrogen atoms as seen from the central oxygen atom (bending mode) (Credit: ISOCAM/SWS / A. Boogert et al.)

the centre of our Galaxy. There, an abundance of 10 molecules of water per million hydrogen molecules was derived over a region 150 times larger than in Orion. NASA's Submillimetre Wavelength Astronomical Satellite (SWAS) – launched after ISO – probed cooler regions, providing the measure of 10^{-8} (10 molecules of water per billion hydrogen molecules) in quiescent clouds.

What happens to the newly formed water molecules? They survive the imminent destruction from the strong ultraviolet radiation emitted by the embryonic star, thanks to the shielding provided by the dust. Away from the star, water molecules stick onto grains as ice. This cosmic 'dirty snow' will then stay in the same system or travel in space until it is eventually incorporated into the formation of another stellar system.

YSOs (Young Stellar Objects)

Once a star is born, it is called a YSO (Young Stellar Object) by astronomers. The dust in the surroundings of the star is heated to a few hundred degrees, thus providing a continuum against which the cooler foreground species can be seen in absorption. An example is provided by the ISO spectrum of Elias 29 (Fig. 3). The water ice bands at wavelengths of 3 and 6 microns dominate the spectrum. Fingerprints of many other species are present. In fact, ISO has provided the first complete, unbiased census of a variety of interstellar ices, thus giving an important impetus to laboratory research for the correct interpretation of the spectra. Water in the gas phase is also detected, closer in to the star where the temperature is high enough to expel the water from the grains or to trigger further formation of water molecules. ISO has observed water lines in a number of YSOs (Fig. 4). The derived abundances for the gas and solid phases show a dependence on temperature, which points to different evolutionary stages as the envelopes expand and cool. The ISO observations thus put constraints on the models developed for

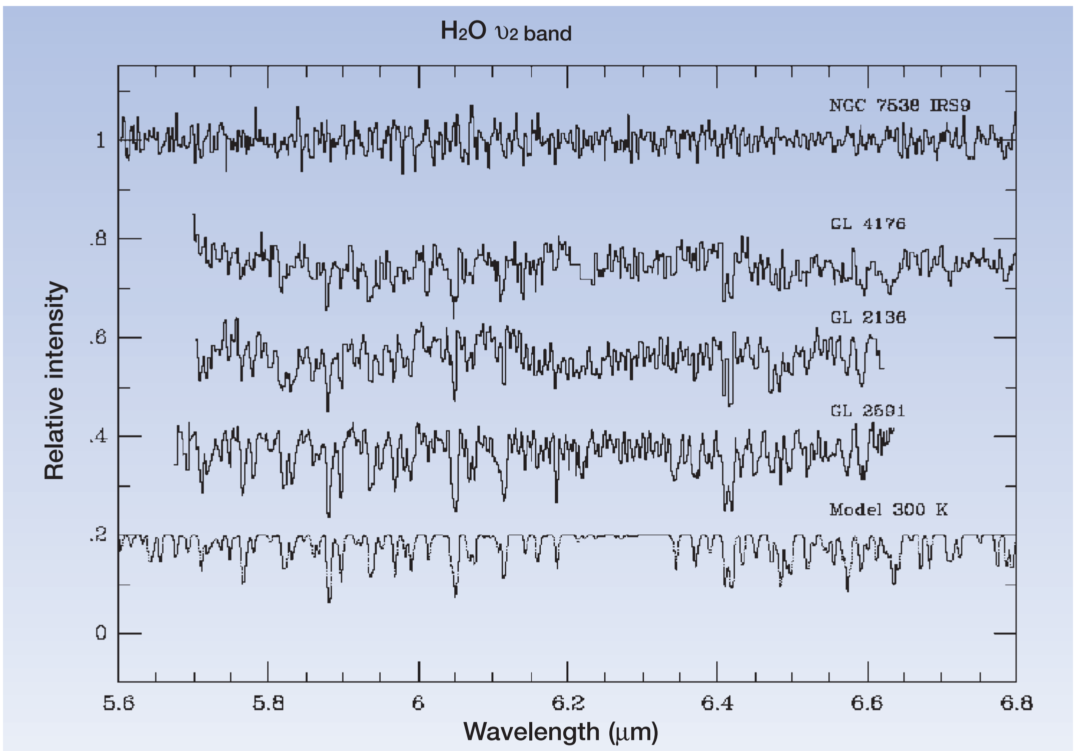
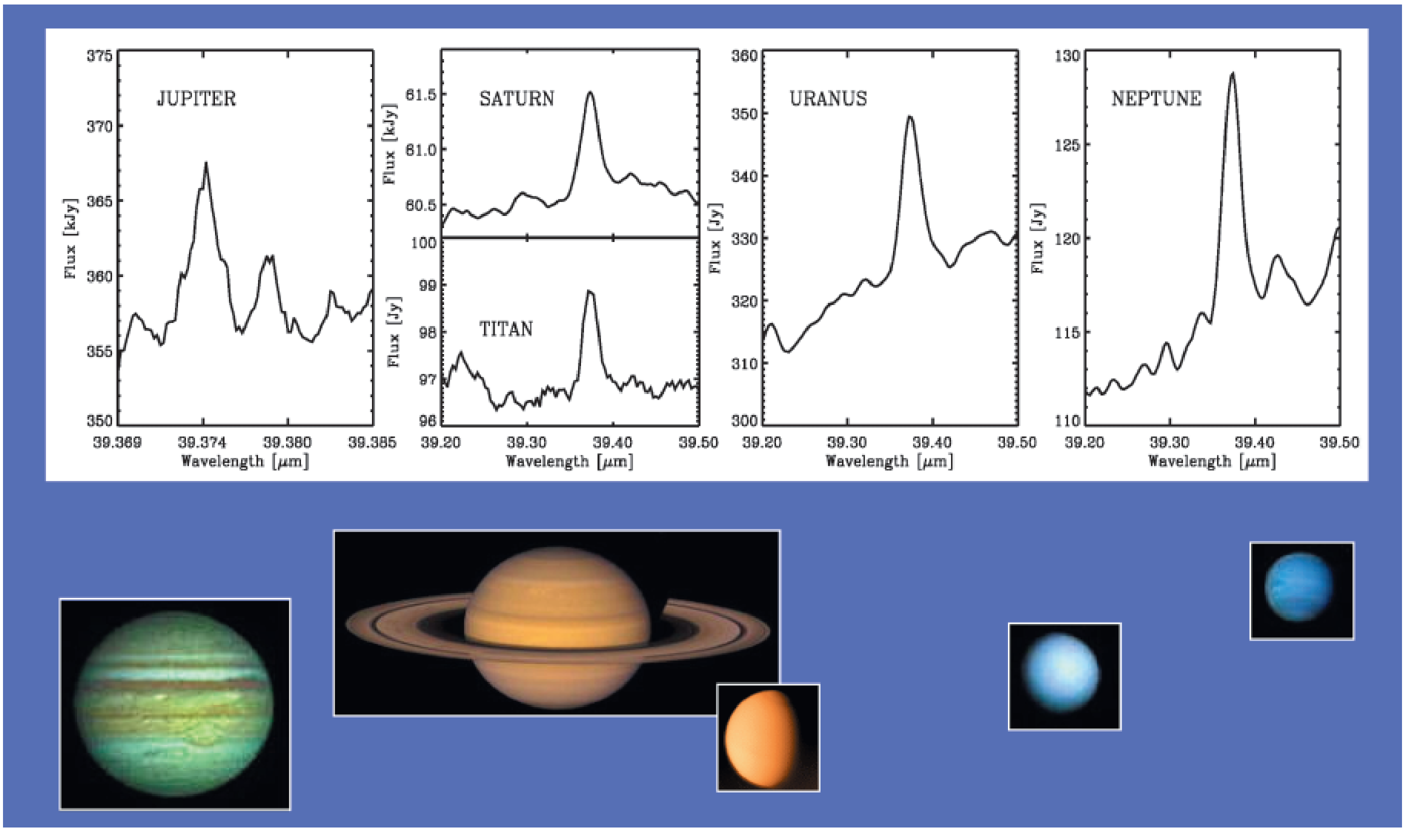


Figure 4. Spectra of a few YSOs in the bending mode band of water at 6 micron. Note how well the observed spectra (first 4 rows) are matched by the model (last row), which assumes warm (300 K) water vapour (Credit: SWS / E. van Dishoeck & F. Helmich)



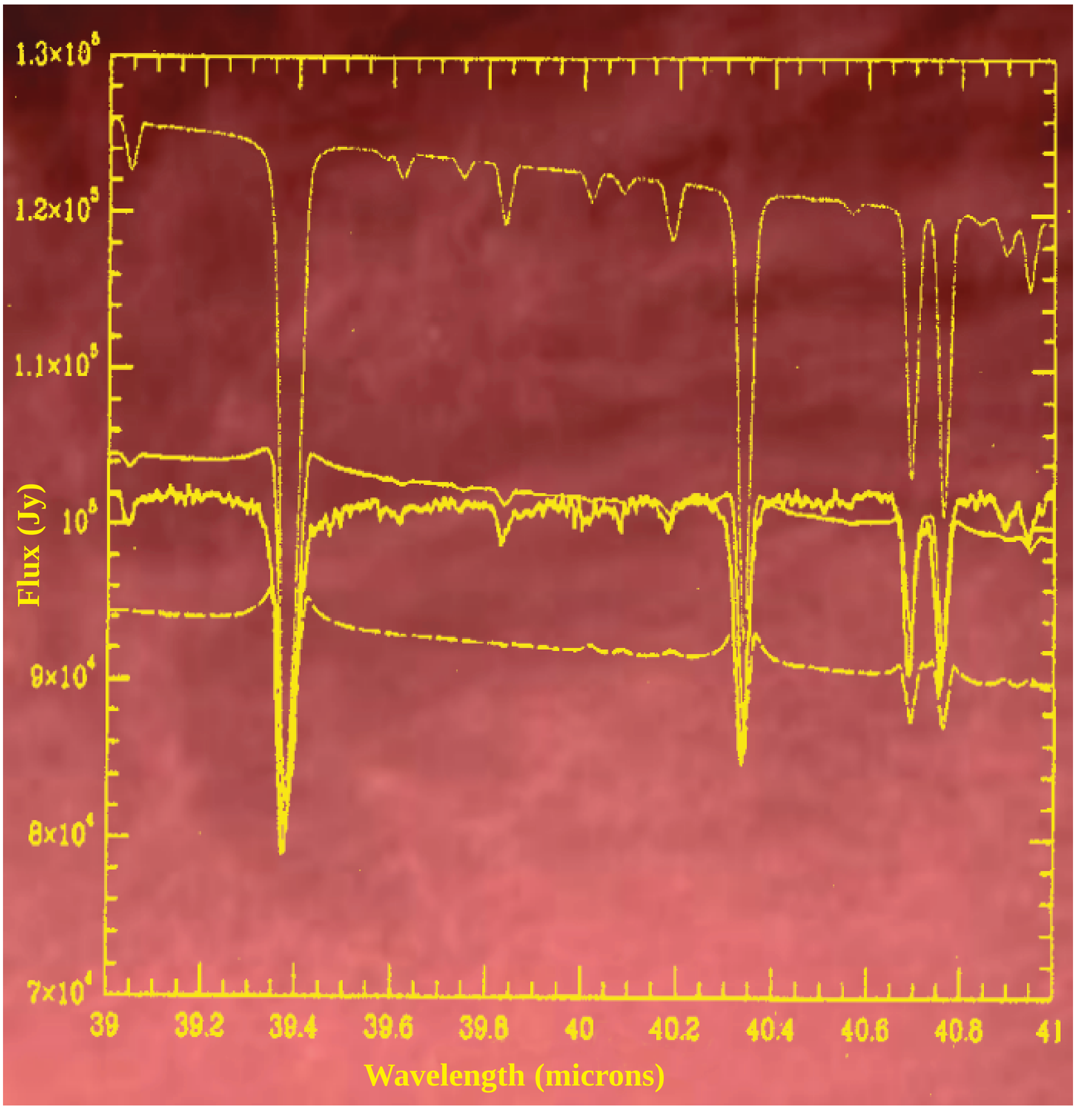


Figure 5. Detection of water vapour in the upper atmospheres of the Giant Planets and Saturn's moon Titan
(Credit: SWS/ H.Feuchtgruber, Th. Encrenaz, A. Coustenis et al.)

Figure 6. ISO detections of water lines in the Martian atmosphere, overlaid on a Mars Pathfinder image of Martian clouds. The ISO results are best modelled with a tenuous (~15 ppt-micron) layer of water clouds located close to the surface (~13 km altitude), thus confirming the results obtained by Mars Pathfinder
(Credit: SWS / Th. Encrenaz et al., NASA / Pathfinder)

YSOs, determining the relative contributions of the envelopes and shocks as water formation carriers. It is interesting to note the similarity in the composition of YSOs and cometary ice, for instance in W33A and Comet Hale-Bopp, which exhibit 82% and 72% water ice, respectively.

Formation of planets

Planets appear to form through an agglomeration of material from the surroundings of a newly born star. The remaining dust (not processed into planets) would remain at the outskirts of the newly formed solar system, containing water ice. Let's confront this theory with the ISO observations of the Solar System.

Our Solar System

The most surprising results from the ISO observations of the Solar System are the detection of water in the upper atmospheres of all of the giant planets and on Saturn's moon Titan (Fig. 5). Water has also been detected close to Mars' surface (Fig. 6). Indeed, water is expected to have been present in the Solar System since its formation, as we have seen that water is abundant in the Interstellar Medium. However, the water incorporated in the planets is expected to condense in clouds, as we see on Earth. Therefore, there must be an external source of water. The similar influx observed for the giant planets and Titan favours a real external source, although the sputtering of the icy rings could also play a role; the influx of water (which on Saturn is of order 4 – 70 kg/s) is attributed to interplanetary dust and comets. An example of such impacts is provided by Comet Shoemaker-Levy 9, which broke-up and impacted in Jupiter's atmosphere in 1994, releasing 2 million tons of water.

Comets are distributed in two groups: the short-period comets, believed to originate in the region close to Neptune's orbit (the so-called 'Kuiper Belt'); and the long-period comets, believed to come from a sphere at a radius of about 50 000 AU (the so-called 'Oort Cloud'). Being so far away from the Sun, comets are believed to maintain the pristine composition of the pre-solar nebula. ISO observed comets from both groups, detecting water, CO and CO_2, with gas production rates increasing as the comets were approaching the Sun, as expected. Water ice has also been observed, and the gas and ice production rates are similar, pointing to a scenario in which the water vapour comes from the evaporation of ice. The water released by Comet Hale-Bopp was measured by ISO at 2.9 AU to be 10 ton/s (Fig. 7).

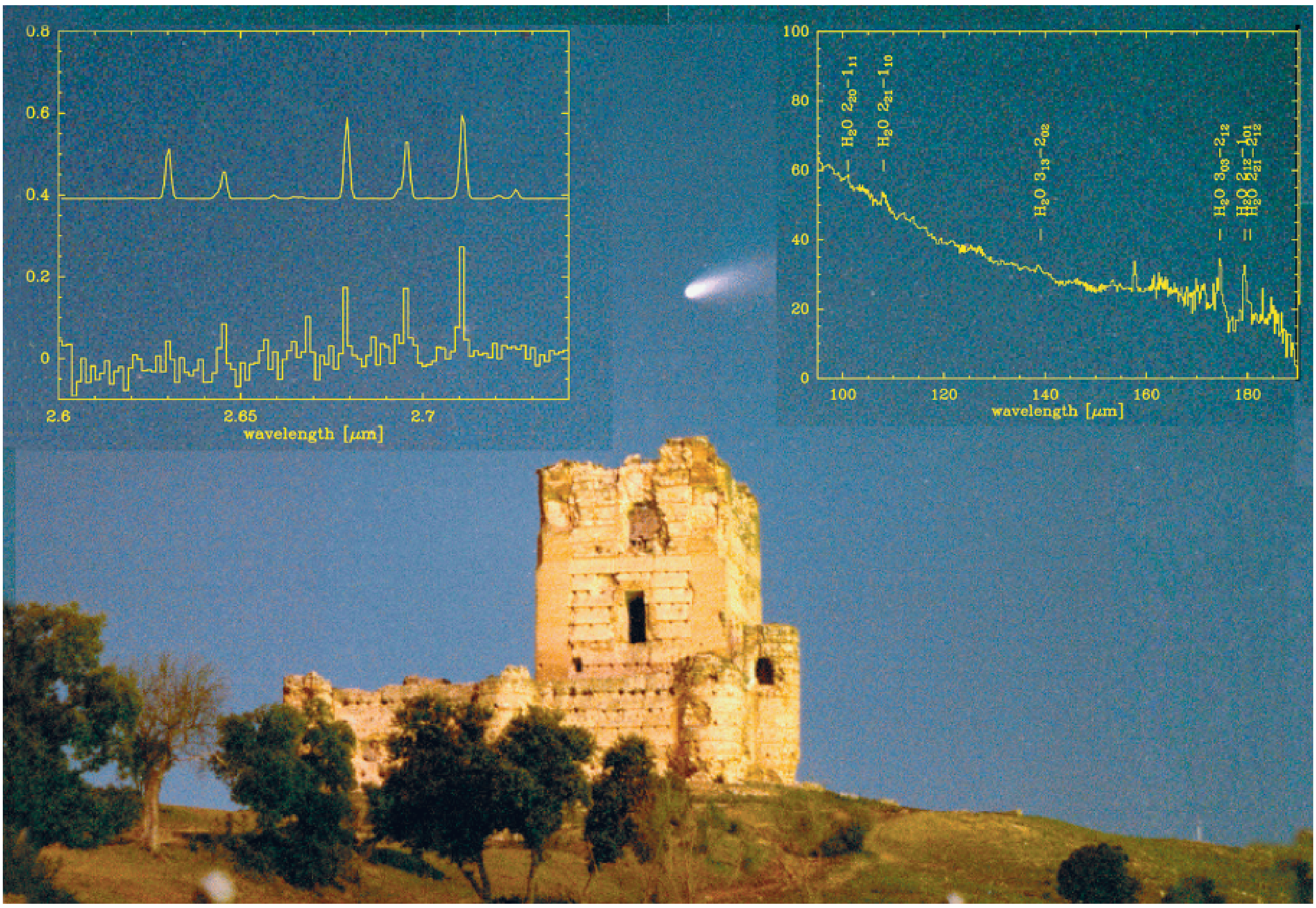
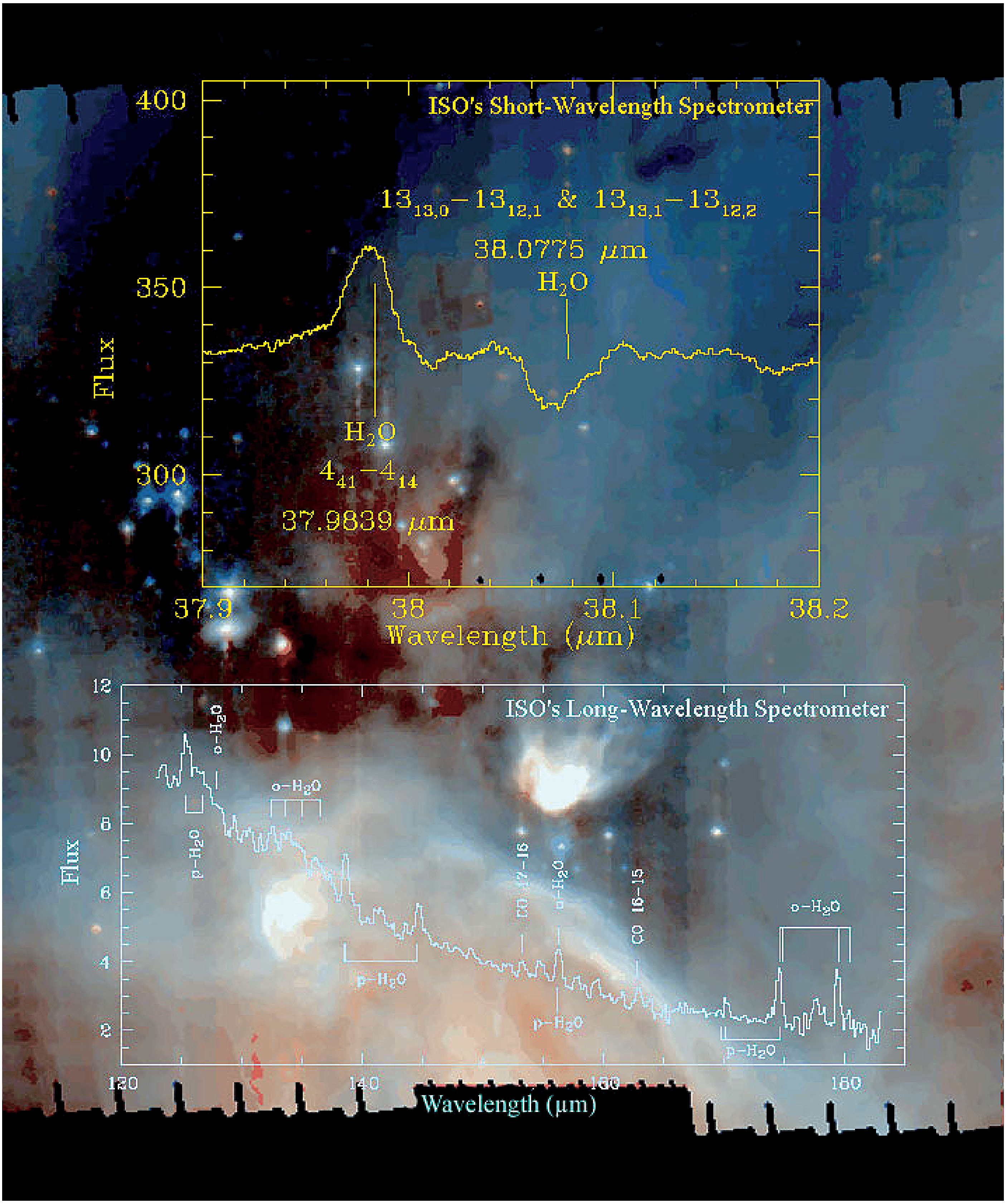


Figure 7. SWS and LWS spectra of Comet Hale-Bopp, showing various lines of water vapour (Credit: SWS / LWS / J. Crovisier et al.) The background image shows the comet above the castle at ESA's VILSPA ground station near Madrid, from which ISO was operated (Credit: K. Leech)



ISO observations therefore address the question of the origin of water on Earth. The scenario by which water originates from the impact of external bodies is gaining weight, while some water could also have been released by the inner rocks in the form of steam during the numerous volcanic eruptions on the young planet Earth. The influx of water currently inferred from ISO observations of the giant planets and Titan is compatible with the observed influx of interplanetary dust (also of cometary origin) at 1 AU. The amount of water present on Earth is compatible with an impact frequency for large comets on Earth equivalent to about 1 impact per millennium over the first billion years of the Solar System, which is not unreasonable.

Figure 8. Detection of water vapour in the vicinity of stars: W Hydrae (Credit: SWS /LWS / M. Barlow et al.) In the background, an ISOCAM image of the dark star-forming region Rho Ophiuchi.

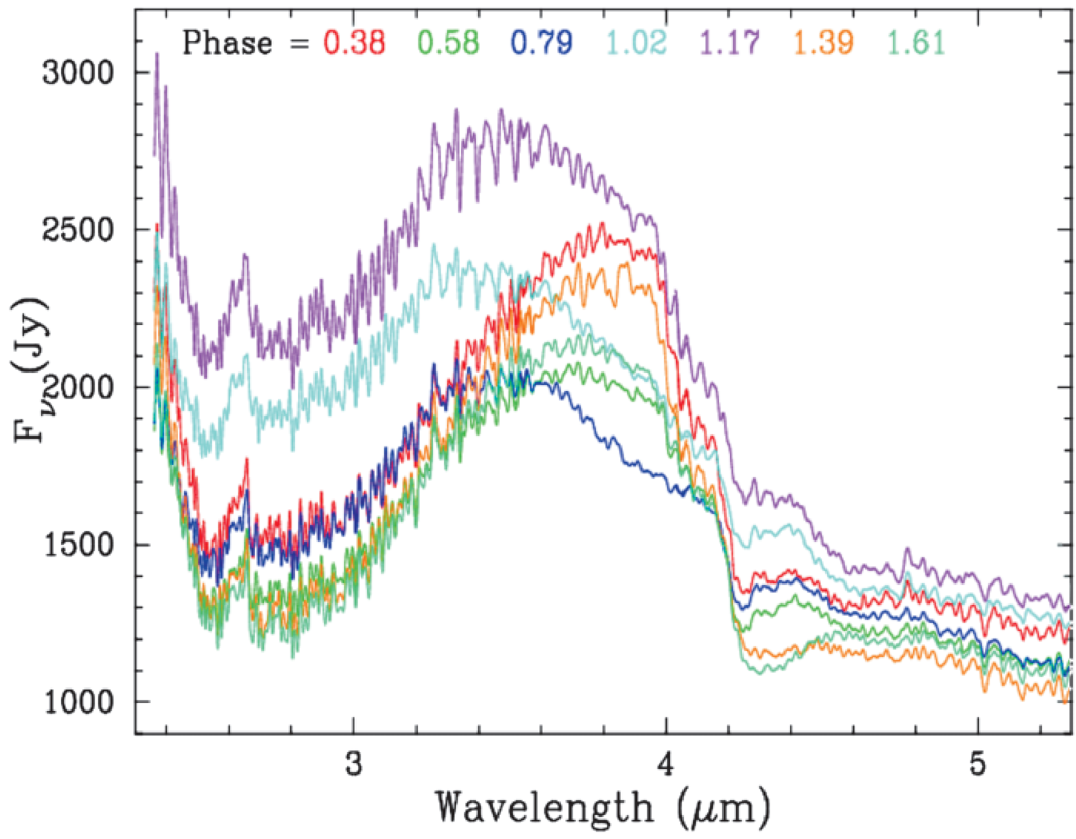


Figure 9. The water spectrum in T Cep shows a variation that correlates with the star pulsation (Credit: SWS / I . Yamamura, M. Matsuura, T. Tsuji et al.)

What happens to water when a star dies?

When the hydrogen fuel becomes depleted in the interior of a star, more is used from the outer parts. This starts a process of expansion of the star, until it becomes a red giant. It is expected that this will occur with our Sun in 5 billion years' time. One of the last evolutionary stages of stars with low to intermediate masses (ranging from one to eight times the mass of the Sun) is called the Asymptotic Giant Branch (AGB). In the AGB phase, stars are red giants with effective temperatures of typically 3000 deg and radii several hundred times the radius of the Sun. The star's structure is very complicated, with several layers of different compositions, resulting in tremendous instabilities. Quite often, AGB red giants are observed as variable stars, like the star Mira, which vary in the visible by several magnitudes with periods of typically one year. These stars lose mass into the Interstellar Medium via the pulsation mechanism, with rates ranging from one E-7 to E-4 solar masses per year at velocities of 36 000 km/h.

ISO has detected water lines in the outer atmospheres of several AGB stars (e.g. W Hya, shown in Fig. 8) and, unexpectedly, also around a hotter star (μ Cep). This is best modelled assuming concentrations of hot (1000–2000 K) water vapour located a few stellar radii from the star. In some cases, the water emission appears to follow the stellar pulsation (Fig. 9). ISO's detection of water around stars is forcing theoreticians to expand their stellar modelling to the outer layers, by means of dynamical models.

The future

ISO has provided – for the first time – a complete overview of the incredibly rich spectroscopy in the infrared and has shown the ubiquitous presence of water in space, even in other galaxies such as Arp 220, but this is only the 'tip of the iceberg'. More details and, possibly surprises, remain to be found in the ISO data, even as other facilities are being prepared. Greater detail and better spatial and spectral resolution (providing more information on the dynamics) are expected to come from the ESA Cornerstone FIRST mission (to be launched in 2007), SIRTF (2002 launch), SOFIA (to be operated from 2002), and NGST (2009).

Acknowledgement

The results described above are the work of a large number of astronomers, who for reasons of readability have not been individually credited throughout the article. The world-wide astronomical community is also thanked by the authors for their enthusiastic use of ISO data, without which this article would not have been possible.