

SOLAR SYSTEM

Jupiter's elusive water

Microwave measurements of water vapour from the Juno spacecraft show that Jupiter is enhanced in oxygen by roughly three times the solar abundance at the equator. The water abundance is important in understanding the formation of Jupiter, the structure of its deep interior, and the nature of its clouds and weather.

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Since Jupiter is composed primarily of H_2 , nearly all of its oxygen is in the form of H_2O . Like on Earth, H_2O on Jupiter condenses to form water clouds. Unlike on Earth, these clouds are hidden beneath upper clouds composed of ammonia (NH_3) and ammonium hydrosulfide (NH_4SH). Water vapour on Jupiter has been measured from Earth but the presence of Jupiter's clouds and radiation belts complicate the interpretation of its deep abundance. The Juno spacecraft is equipped with a microwave radiometer (MWR) that measures thermal radiation from the deep atmosphere. Non-thermal radiation is minimized because it flies below the radiation belts in an elliptical polar orbit. Writing in *Nature Astronomy*, Li and collaborators¹ report measurements of H_2O from Juno indicating that Jupiter is enhanced in oxygen by roughly three times the solar abundance at the equator.

Water vapour on Jupiter was first detected at thermal-infrared wavelengths using NASA's Kuiper Airborne Observatory². Later, infrared spectrometers on the Voyager³ and Galileo⁴ spacecraft measured H_2O on Jupiter; however, most of their measurements were confined to relatively cloud-free regions where the infrared signal was strongest at 5 μm . Jupiter has alternating latitude bands consisting of belts with thin dark clouds and zones with much thicker white clouds. Jupiter appeared to be depleted in water⁵ in both belts and zones compared with the solar value of O/H; however, this conclusion was dependent on the assumed cloud model, which was valid for belts but not for zones⁶.

The definitive value for the O/H ratio on Jupiter was expected to be determined by the Galileo Probe, which parachuted into Jupiter in December 1995. The Galileo Probe measured a depletion in H_2O vapour (O/H was 0.5 times solar⁷ at a pressure of 20 bar⁸) and it did not detect a thick water cloud during its descent⁹. This was a puzzling result. If these measurements were representative of Jupiter as a whole, it would be difficult to understand how a dry

Jupiter devoid of thick water clouds could be formed, given that water is abundant in the neighbourhood in the form of Jupiter's icy moons. Another clue that Jupiter has abundant water came from observations of lightning on Jupiter's night side, which originated at the level of the expected water clouds¹⁰. A consensus emerged that the probe had landed in an anomalously dry¹¹ region of Jupiter, known as a 5- μm hot spot¹². It was as if aliens had sent a probe to Earth to measure water and it landed in the Sahara Desert rather than in the Pacific Ocean. Thus, the next mission dedicated to Jupiter, Juno, was equipped with instrumentation to map water from orbit in order to solve this mystery.

The Juno spacecraft¹³ arrived at Jupiter in July 2016 and was placed into an elliptical polar orbit with a period of 53 days. Li et al. used a technique, microwave radiometry, to measure H_2O that is not biased towards regions with very low cloud opacity. Microwaves penetrate very deep into Jupiter's atmosphere and are not sensitive to cloud opacity. At closest approach, Juno flies between the inner radiation belts and the planet's atmosphere to minimize non-thermal emission from the magnetosphere that would otherwise overwhelm the microwave signal from the deep atmosphere. Juno's MWR has six channels from 0.6 GHz (50 cm) to 22 GHz (1.37 cm) that sound from 0.7 to 1,000 bar on Jupiter¹⁴. Figure 1 shows a JunoCam image of Jupiter's equatorial zone showing thick clouds that block infrared radiation but allow microwaves to penetrate with ease, thus allowing Juno to probe deep into the atmosphere.

Measuring water with microwave radiometry is still very difficult. First, non-thermal emission from Jupiter's radiation belts must be subtracted out. Next, H_2O is not the main absorber at radio wavelengths: ammonia absorption is much stronger. It was therefore necessary to measure the vertical profile and latitudinal distribution of NH_3 before tackling H_2O . The simplest profile of NH_3 is near the equator, where the



Fig. 1 | JunoCam wide-angle image of Jupiter's equator acquired at an altitude of 5,630 km on 16 December 2017. Thick white clouds are present in Jupiter's equatorial zone, which complicates the interpretation of infrared measurements of water. At microwave frequencies Jupiter's clouds are transparent, allowing Juno's MWR to measure water vapour as deep as 20 bar in the equatorial zone. Credit: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill

abundance is constant with height at 360 ppm¹⁵. Thus, Li et al. report the abundance of water on Jupiter at a latitude where we understand the behaviour of NH₃ the best.

Li et al. measured the H₂O abundance in the equatorial zone corresponding to an enhancement in O/H of $2.7^{+2.4}_{-1.7}$ times solar. This value supports the idea of a constant heavy element enrichment factor of three to four times solar for carbon, nitrogen and oxygen. It allows us to exclude models in which Jupiter was formed from planetesimals depleted in water and enriched in carbon¹⁶. It also rules out models in which volatiles are trapped in a clathrate hydrate, because they predict O/H enrichments of at least ten times solar¹⁷. Enhanced water supports the idea that lightning originates from deep water clouds, rather than in the upper ammonia clouds.

Juno measured water at a different location but at roughly the same pressure as the Galileo Probe. MWR found five times as much H₂O as the probe had measured. Meanwhile, ground-based measurements of water indicate an O/H ratio of at least 1.1 times solar¹⁸. These data confirm what was suspected, namely, that the Galileo Probe landed in an unusually dry region. The search for abundant water was a long time coming, but it was worth the wait. There is more to come. Plans for Juno to measure water at additional latitudes and improved lab work may reduce the size of the uncertainties in future measurements.

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