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# Deuterium-enriched water ties planet-forming disks to comets and protostars

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Water is a fundamental molecule in the star and planet formation process, essential for catalysing the growth of solid material and the formation of planetesimals within disks<sup>1,2</sup>. However, the water snowline and the HDO:H<sub>2</sub>O ratio within proto-planetary disks have not been well characterized because water only sublimates at roughly 160 K (ref. <sup>3</sup>), meaning that most water is frozen out onto dust grains and that the water snowline radii are less than 10 AU (astronomical units)<sup>4,5</sup>. The sun-like protostar V883 Ori ( $M_* = 1.3 M_\odot$ )<sup>6</sup> is undergoing an accretion burst<sup>7</sup>, increasing its luminosity to roughly 200  $L_\odot$  (ref. <sup>8</sup>), and previous observations suggested that its water snowline is 40–120 AU in radius<sup>6,9,10</sup>. Here we report the direct detection of gas phase water (HDO and H<sub>2</sub><sup>18</sup>O) from the disk of V883 Ori. We measure a midplane water snowline radius of approximately 80 AU, comparable to the scale of the Kuiper Belt, and detect water out to a radius of roughly 160 AU. We then measure the HDO:H<sub>2</sub>O ratio of the disk to be  $(2.26 \pm 0.63) \times 10^{-3}$ . This ratio is comparable to those of protostellar envelopes and comets, and exceeds that of Earth's oceans by 3.1 $\sigma$ . We conclude that disks directly inherit water from the star-forming cloud and this water becomes incorporated into large icy bodies, such as comets, without substantial chemical alteration.

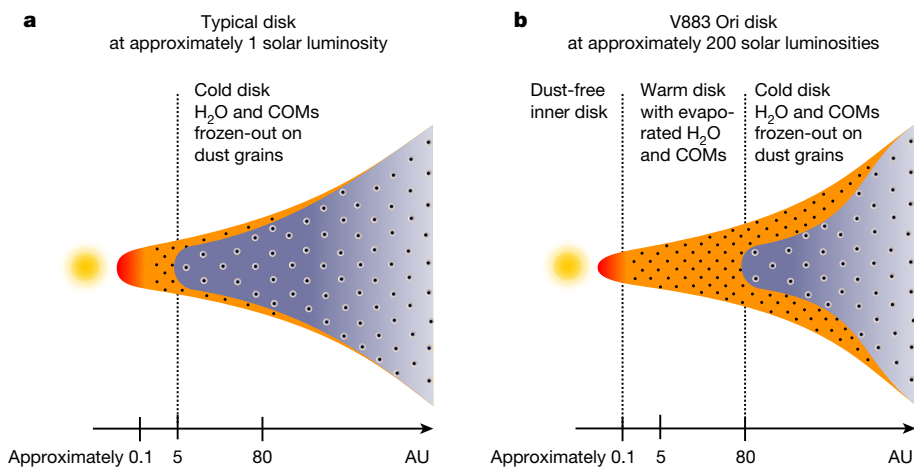
We observed V883 Ori (located in the Orion molecular clouds) using the Atacama large millimetre/submillimetre array (ALMA) at roughly 0.1'' resolution (40 AU diameter at its distance of 400 pc; ref. <sup>11</sup>). The full extent of the proto-planetary disk surrounding V883 Ori is well-resolved in our observations, with the dust and gas emission extending to roughly 125 and 320 AU, respectively<sup>6</sup>. The disk around V883 Ori is young, similar to the well-known HL Tau system<sup>12</sup>, and the disk mass of roughly 0.02–0.09  $M_\odot$  is about ten times greater than the surrounding envelope mass<sup>6,13</sup>. The accretion burst (which may have begun more than 130 years ago<sup>7,14</sup>) has heated a large fraction of the disk above the sublimation temperature of water, and we illustrate how V883 Ori and a more typical proto-planetary disk differ in Fig. 1.

We detect three emission lines of gas phase water in the disk of V883 Ori: HDO at 225.89672 and 241.561550 GHz and H<sub>2</sub><sup>18</sup>O at 203.40752 GHz (Methods). The HDO and H<sub>2</sub><sup>18</sup>O kinematics are consistent with Keplerian rotation (Extended Data Figs. 1 and 2). The emission from all three lines peak at a radius of 50 to 60 AU, but extend to roughly 160 AU (Fig. 2 and Extended Data Fig. 3). HDO is substantially brighter than H<sub>2</sub><sup>18</sup>O (despite the D:H ratio less than 1) owing to the ratio of <sup>16</sup>O:<sup>18</sup>O and its molecular properties (Methods). The structure and extent of the water emission is very similar to complex organic molecules (COMs), such as methanol<sup>9,15</sup>, which makes sense given that methanol is expected to

sublimate at a similar temperature (roughly 130 K)<sup>3</sup>. C<sup>17</sup>O, however, is more extended than water and methanol because it sublimates at around 25 K (ref. <sup>16</sup>) (Fig. 2). The apparent depression of emission in the centre of some images in Fig. 2 is due to the opacity of the continuum, absorbing gas emission at radii less than 40 AU. The high dust optical depth at smaller radii, even for more-evolved disks<sup>17</sup>, may obscure molecular line emission coming from the disk midplane and make the midplane water emission of lower luminosity systems difficult to characterize.

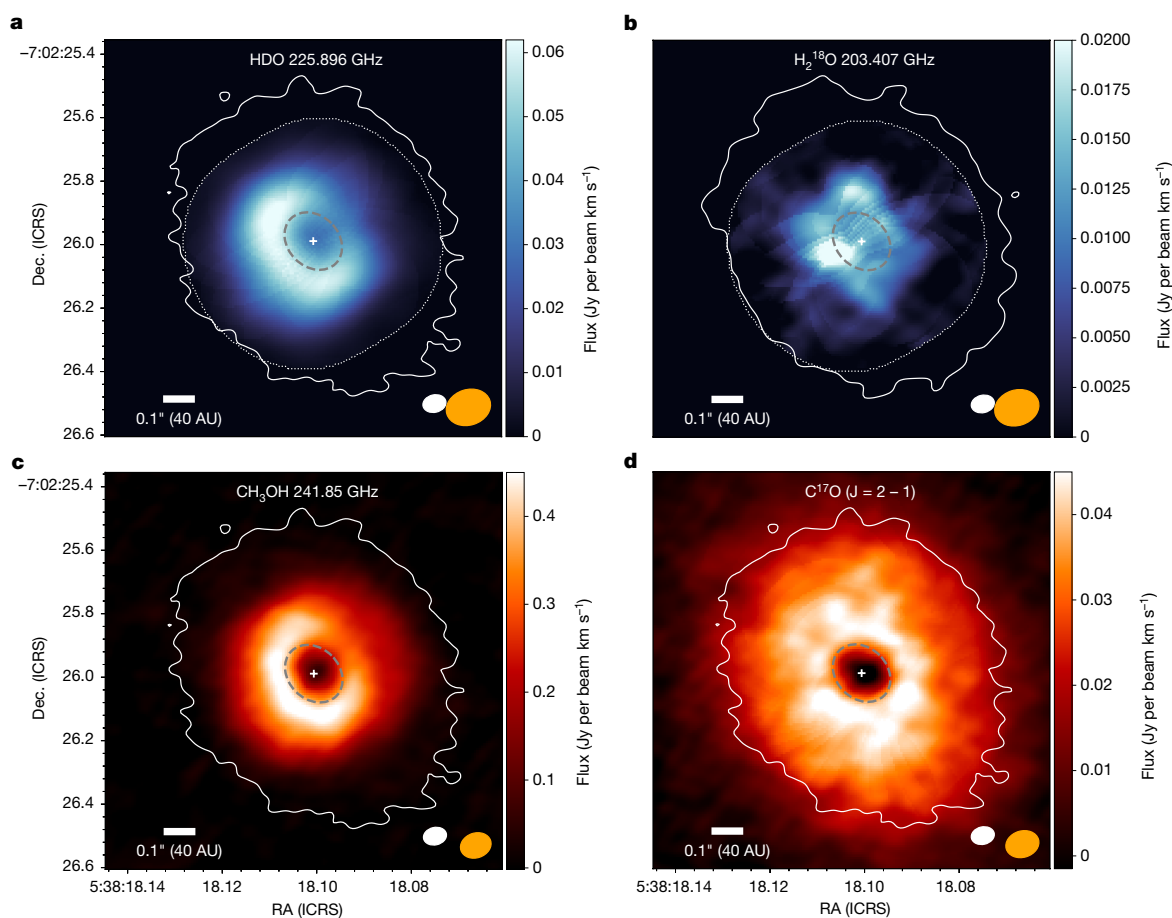
The warm nature of V883 Ori's disk enables us to characterize its water reservoir with spatially resolved observations, unlike most proto-planetary disks (Fig. 1)<sup>18</sup>. We measured the column densities of HDO and H<sub>2</sub><sup>18</sup>O in several ways to test the robustness of our measurements (Methods). For our primary method, we extracted the integrated spectra within a 0.4'' (160 AU) radius to measure the total flux of the emission lines (Extended Data Fig. 4). We also extracted radial intensity profiles from the integrated intensity maps in Fig. 2 using Keplerian masks. The spectral extraction method yields a disk-averaged measurement, whereas the integrated intensity method yields the measurements as a function of disk radius. The integrated fluxes of the HDO lines are  $0.644 \pm 0.028$  and  $0.595 \pm 0.037$  Jy km s<sup>-1</sup> for the 225 and 241 GHz lines, respectively, whereas the H<sub>2</sub><sup>18</sup>O line flux is  $0.126 \pm 0.025$  Jy km s<sup>-1</sup>.

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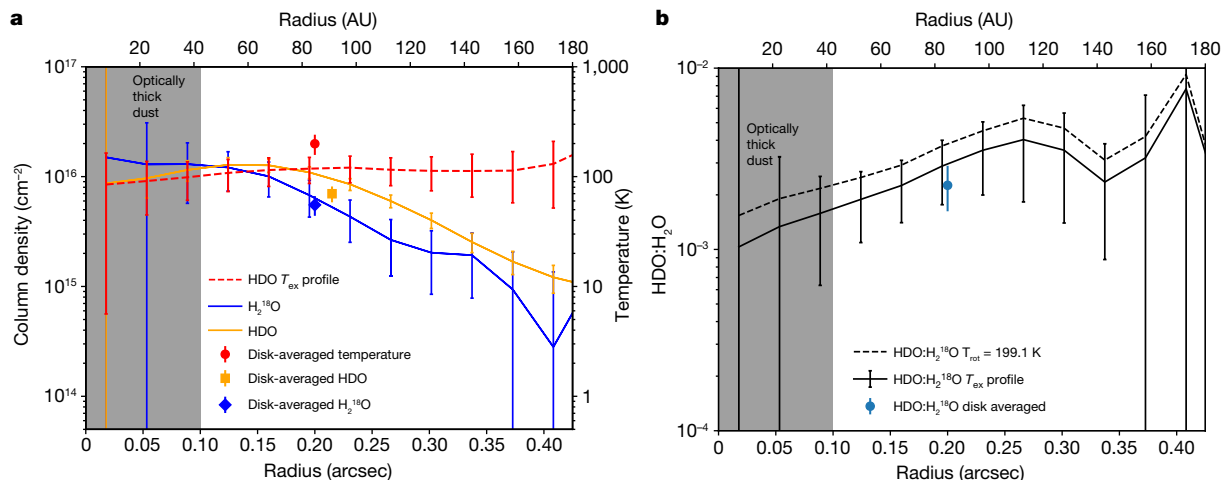
**Fig. 1 | Illustrations comparing a typical proto-planetary disk and the disk surrounding the outbursting protostar V883 Ori. a**, A typical disk in which water and COMs are frozen out onto dust grains at most radii except the very inner disk. **b**, The case of V883 Ori in which the disk has a much larger region where water and COMs are sublimated from the dust grains, enabling the water

and COM emission to be detected and resolved. Orange and red regions denote the warmer regions of the disk where the ices are sublimated and the light blue/grey denotes the colder regions where the water and COMs are frozen out. The black points alone denote dust grains with no ice coating, whereas the black points with grey circles around them denote icy dust grains.



**Fig. 2 | Integrated intensity images of water and other molecular lines in the disk of V883 Ori. a–d**, We show the HDO 225 GHz line (a), the  $\text{H}_2^{18}\text{O}$  203 GHz line (b),  $\text{CH}_3\text{OH}$  (c) and  $\text{C}^{17}\text{O}$  (d), as the colour scale, whereas the outer extent of the dust continuum emission is shown as a white contour; the integrated intensity maps were extracted from the data using the Keplerian masks whose outer extent are marked as dotted lines in a, b. The white cross marks the location of the continuum emission peak and the position of the protostar. The HDO and  $\text{H}_2^{18}\text{O}$  lines show emission that is smaller in radial extent than the continuum and  $\text{C}^{17}\text{O}$  emission. The  $\text{CH}_3\text{OH}$  (methanol) image shows a very similar structure and extent relative to the HDO and  $\text{H}_2^{18}\text{O}$  lines.  $\text{C}^{17}\text{O}$  more fully traces the extent of the disk gas emission with its lower sublimation

temperature of roughly 25 K, extending beyond the continuum emission. The central depression in emission for all lines is the result of optically thick continuum emission attenuating the molecular emission at radii smaller than roughly 40 AU ( $0.1''$ ); the extent of this optically thick region is denoted with the dashed thick grey line in the centre of each image. The depression is less obvious for  $\text{H}_2^{18}\text{O}$  in b due to its lower signal to noise ratio and some contamination of its integrated intensity map from a neighbouring line. The ellipses in the lower right corner denote the resolution of the line observations (orange, roughly  $0.1''$ ) and the continuum (white, roughly  $0.08''$ ). Dec., declination; ICRS, International Celestial Reference System; RA, right ascension.



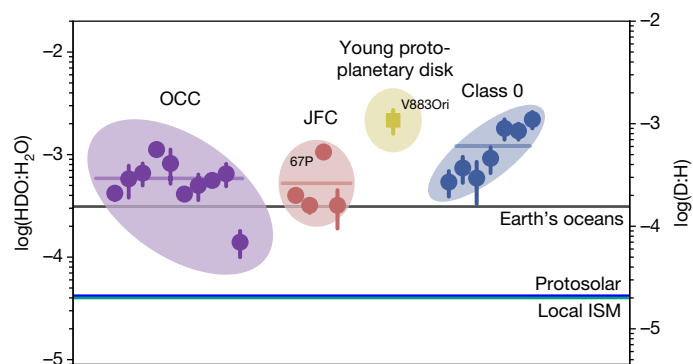
**Fig. 3 | Radial column density measurements of water and the HDO:H<sub>2</sub>O ratio along with their disk-averaged measurements. a,b.** The radial column density profiles of HDO and H<sub>2</sub><sup>18</sup>O (a) and the HDO:H<sub>2</sub>O ratio as a function of deprojected radius in the disk of V883 Ori (b). The disk-averaged values are plotted at 0.2" in both panels. The HDO column density is the average of the column density derived from the two HDO transitions (this only reduces the uncertainties because the HDO column density will be identical for the two transitions). The HDO column densities have some contamination from a neighbouring COM line for the 241 GHz transition, which has been quantified in the Methods. This contamination could affect the temperature and the HDO:H<sub>2</sub>O profile, but the overall effect is small as shown by the agreement with

The ratio of the upper level column densities for the two HDO lines is used to estimate the water excitation temperature ( $199 \pm 42$  K). This temperature is used to derive the column densities for HDO and H<sub>2</sub><sup>18</sup>O of  $(6.98 \pm 1.15) \times 10^{15}$  and  $(5.52 \pm 1.13) \times 10^{15}$  cm<sup>-2</sup>, respectively. The H<sub>2</sub><sup>18</sup>O column density translates to a H<sub>2</sub>O column density of  $(3.09 \pm 0.70) \times 10^{18}$  cm<sup>-2</sup> (Methods). The radial column density profiles of HDO and H<sub>2</sub><sup>18</sup>O are shown in Fig. 3 and are consistent with the disk-averaged measurements. The midplane water snowline is estimated to be roughly 80 AU, corresponding to the radius at which the HDO and H<sub>2</sub><sup>18</sup>O column density begins to rapidly decline (Fig. 3). The total gaseous water mass in the disk is  $1.69 \times 10^{27}$  g, equivalent to roughly 1,200 Earth oceans. This is a lower limit because it does not include water at radii less than 40 AU or the water ice in the outer disk. Finally, we calculate a disk-averaged HDO:H<sub>2</sub>O ratio of  $(2.26 \pm 0.63) \times 10^{-3}$ , consistent with the HDO:H<sub>2</sub>O radial profile (Fig. 3). The measurements of the HDO:H<sub>2</sub>O ratios from different methods are all consistent within their 1 s.d. uncertainties, demonstrating that the measurement method does not strongly influence the results (Extended Data Table 4).

Water (H<sub>2</sub>O, HDO, and D<sub>2</sub>O) is expected to form as ice mantles on dust grains in the cold interstellar medium (ISM) through grain surface reactions. The abundance of deuterated species becomes enhanced in the cold ISM due to deuterium becoming locked into H<sub>2</sub>D<sup>+</sup>, and the dissociative recombination of deuterium bearing molecules increases the free deuterium available for HDO and D<sub>2</sub>O formation within ice mantles<sup>18,19</sup>. The HDO:H<sub>2</sub>O ratio in ice mantles is not well-constrained, only upper limits of roughly 10<sup>-2</sup> are available<sup>20</sup>. However, within the warm gas at small radii around Class 0 protostars, where these ices have sublimated, the HDO:H<sub>2</sub>O ratios are found to be between roughly  $6 \times 10^{-4}$  and  $2 \times 10^{-3}$  (refs. 21–23). Then comets range from  $3 \times 10^{-4}$  to  $10^{-3}$  (refs. 24,25), and Earth's oceans are  $3.11 \times 10^{-4}$  (Extended Data Table 5). The HDO:H<sub>2</sub>O ratios for V883 Ori and these different objects are summarized in Fig. 4.

The HDO:H<sub>2</sub>O ratio of V883 Ori is comparable to the youngest (Class 0) protostars<sup>22</sup>, and then compared to more-evolved objects that formed within the Solar System, V883 Ori's HDO:H<sub>2</sub>O ratio is also similar to many Oort Cloud comets and 67P from the Jupiter Family

comets (Fig. 4). This makes sense because comets are icy relics that are expected to have formed in the outer parts of the proto-planetary disk. It is important to note that it was previously thought that the Jupiter Family and Oort cloud comets formed at different locations in the Solar



**Fig. 4 | HDO:H<sub>2</sub>O ratio for Class 0 protostars, V883 Ori, Jupiter Family comets (JFC, with 67P labelled), Oort Cloud comets (OCC), Earth's oceans, the Sun and the local ISM.** The points are arranged to highlight a potential evolutionary scenario with the forming protostars on the right, the 'evolved' Solar System bodies on the left, and V883 Ori fills in a region of parameter space for a young proto-planetary disk, just before or contemporaneous with planet formation. The ellipses drawn around the different groups are meant to guide the eye, but the horizontal lines within each ellipse denote the mean HDO:H<sub>2</sub>O ratio for each group, and the vertical lines associated with each point represent the 1 s.d. uncertainties. If a vertical line is not visible, the uncertainty is less than the size of the symbol. In the context of other measurements, V883 Ori indicates that the HDO:H<sub>2</sub>O ratio does not strongly evolve from the protostar phase to the disk, providing further observational evidence that the water is directly inherited from the envelope to the disk without significant chemical changes. Moreover, the HDO:H<sub>2</sub>O ratio of comets are similar to V883 Ori (but slightly below), indicating that the water we probe in the gas phase within the disk of V883 Ori is similar to the water that becomes incorporated into comets. The individual measurements are tabulated in the Methods (Extended Data Table 5).

System, close to the orbits of the giant planets and outside the orbit of Neptune, respectively. It is now thought that the populations are mixed<sup>26</sup>, but their HDO:H<sub>2</sub>O ratios should reflect their original formation location. However, Earth's oceans and some comets have a lower HDO:H<sub>2</sub>O compared to V883 Ori, indicating that the water in those bodies may have undergone further processing at high temperatures, lowering their HDO:H<sub>2</sub>O ratios. Or, the HDO:H<sub>2</sub>O ratio is intrinsically lower in the bodies responsible for water delivery to Earth.

Indeed, it has been shown that outbursts can lower the HDO:H<sub>2</sub>O ratio in the inner 1 to 3 AU of a disk through a combination of high gas temperature (greater than 500 K), radial mixing and isotope exchange reactions in the gas phase ( $\text{HDO} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{HD}$ )<sup>27</sup>. However, this fast evolution of the gaseous HDO:H<sub>2</sub>O ratio is only taking place at radii smaller than we can probe in V883 Ori (and inside the optically thick dust). Conversely, at radii greater than 10 AU, the lower temperature (200–300 K) and densities mean that the isotope exchange reactions are extremely slow; it would take greater than 100 Myr to significantly change the observed HDO:H<sub>2</sub>O ratio in V883 Ori<sup>28</sup>. This means that V883 Ori's HDO:H<sub>2</sub>O ratio is tracing that of water sublimated from the ices. The slowness of the isotope exchange reactions and the fact that HDO is only efficiently created in ice, means that the water emission in V883 Ori, even if it is coming from upper layers of the disk (Fig. 1), is expected to have a similar HDO:H<sub>2</sub>O ratio to the disk midplane.

The HDO:H<sub>2</sub>O ratio within the disk of V883 Ori, at the end of the protostar phase, fills in a crucial gap in the water trail just before or contemporaneous with the formation of large solid bodies within the disk. The relative constancy of the HDO:H<sub>2</sub>O ratio from the protostar phase to the proto-planetary disk indicates that the water within the disk of V883 Ori is directly inherited from the infalling envelope<sup>29–31</sup>. Furthermore, the comet 67P, protostars and V883 Ori<sup>15</sup> all have CH<sub>2</sub>DOH:CH<sub>3</sub>OH ratios that are roughly ten times their HDO:H<sub>2</sub>O ratios. This is further evidence that both water and methanol (and the deuterated species) are formed on icy dust grains, that the molecules are inherited from the prestellar phase, and that significant chemical reset does not occur during disk or comet formation. Some chemical changes are observed from the envelope to disk<sup>32</sup>, but the effect is not strong enough to affect the water and probably other COMs that arrive to the disk as ice<sup>33,34</sup>. Although the specific delivery mechanism of water on Earth remains debated (comets and/or asteroids)<sup>35</sup>, the high D:H found in V883 Ori is evidence that the water molecules in our Solar System originated in the cold ISM before the formation of the Sun<sup>29</sup>. Therefore, spatially resolved water observations towards young planet-forming disks are crucial in linking the water reservoir and the formation of terrestrial planets.

## Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-022-05676-z>.

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## Methods

V883 Ori was observed with ALMA located on Ilano de Chajnantor in Northern Chile in November 2021. Observations were conducted in band 6 (roughly 1.3 mm) and band 5 (roughly 1.5 mm) to target the HDO and  $\text{H}_2^{18}\text{O}$  spectral lines, respectively.

### Band 5 observations

The band 5 observations were conducted with two executions on 3 and 4 November 2021 during C-7 configuration with a maximum baseline length of roughly 3,000 k $\lambda$ , with precipitable water vapour values of 0.72 and 0.78 mm, respectively. There were 41 antennas operating during the first execution and 43 during the second. Each execution was roughly 80 min in duration with roughly 38 min on source per execution for a total time on source in band 5 of roughly 76 min. The monitored quasar J0538-4405 was the absolute flux density and bandpass calibrator in the first execution and J0423-0120 was the flux density and bandpass calibrator in the second execution. Both executions used J0541-0541 as the phase calibrator. The central frequency of the observations was roughly 195.8 GHz and we simultaneously observed many molecular transitions (Extended Data Table 1), but our main focus in this paper is the  $\text{H}_2^{18}\text{O}$  transition at 203.40752 GHz. The absolute flux density uncertainty in band 5 is expected to be roughly 5%.

### Band 6 observations

The band 6 observations were conducted in two consecutive executions on 1 November 2021 during C-7 configuration with a maximum baseline length of roughly 4,000 k $\lambda$ . The measured precipitable water vapour values were 0.74 and 0.77 mm. There were 48 antennas operating during both executions and each execution was roughly 75 min in duration with roughly 40.5 min on source, yielding a total time on source in band 6 of roughly 81 min. Both executions used J0423-0120 as the absolute flux density and bandpass calibrator and J0541-0541 as the phase calibrator. The absolute flux density uncertainty in band 6 is expected to be roughly 5%. The central frequency of the observations was roughly 233.5 GHz and we simultaneously observed many molecular transitions (Extended Data Table 1), but our main focus in this paper is the two HDO transitions at 225.89672 and 241.5615499 GHz. However, we compare to the methanol ( $\text{CH}_3\text{OH}$ ) transitions observed in a separate spectral window with high spectral resolution.

### Data reduction

The data were reduced using the ALMA calibration pipeline within CASA v.6.2.1 (ref. <sup>36</sup>). We used the pipeline-calibrated visibility data and the continuum regions identified by the ALMA pipeline task `hif_findcont` to perform self-calibration on the continuum data and applying the phase and amplitude solutions to the line data as well. Continuum subtraction was also performed using the line-free continuum regions for fitting the underlying continuum using the CASA task `uvcontsub`.

The HDO line at 225 GHz was imaged with the CASA task `tclean` using a robust parameter of 2.0, a channel spacing of 0.162 km s<sup>-1</sup>, an image size of 768 × 768 and a pixel size of 0.0075". All the images used the modified Briggs weighting scheme, set with the `tclean` parameter `weighting='briggsbw taper'`. The resulting beam was 0.104" × 0.082". Then the HDO line at 241 GHz was created using the same image parameters, but with a channel spacing of 0.151 km s<sup>-1</sup> and a beam of 0.098" × 0.077". The  $\text{H}_2^{18}\text{O}$  line at 203 GHz was imaged with the same parameters as the HDO lines, but with a channel spacing of 0.4 km s<sup>-1</sup> due to the lower signal to noise ratio of the line emission compared to the HDO lines; the beamsize for  $\text{H}_2^{18}\text{O}$  is 0.14" × 0.11". The other data cubes, including methanol, were created using the same parameters and their native channel spacing (Extended Data Table 1). To facilitate consistency in the analysis, we generated cubes for each HDO transition that use the same restoring beam as the  $\text{H}_2^{18}\text{O}$  cube and 0.4 km s<sup>-1</sup> channels. This provides a more consistent comparison of the derived radial

profiles for HDO and  $\text{H}_2^{18}\text{O}$  and we use these data with the same channel width and restoring beams exclusively for analysis of the HDO:H<sub>2</sub>O ratio. Finally, aggregate continuum images were created for the band 5 and band 6 data individually, using the line-free regions from all the spectral windows in each band combined. These continuum images had the same image and pixel sizes as the cubes. The synthesized beams of the band 5 and 6 continuum images are 0.11" × 0.088" and 0.073" × 0.055", respectively.

### Analysis

**Keplerian masks.** The presence of other strong emission lines from COMs preclude a simple extraction of spectral line fluxes from the disk of V883 Ori. It is known that  $\text{H}_2^{18}\text{O}$  can be contaminated by nearby  $\text{CH}_3\text{OCH}_3$  (dimethyl ether) lines, and HDO at 225 GHz can be contaminated by  $\text{CH}_3\text{OCHO}$  (methyl formate)<sup>21,22</sup>. Furthermore, HDO at 241 GHz also has contamination, which is likely to come from  $\text{CH}_3\text{CHO}$  (acetaldehyde). Thus, we use Keplerian masks to isolate the HDO and  $\text{H}_2^{18}\text{O}$  emission as best as possible. Keplerian masks select areas within particular channels of a data cube where emission from a Keplerian disk is expected on the basis of the known mass of the protostar. We make use of a Keplerian mask implementation<sup>37</sup> in which various parameters (for example, stellar mass, disk radius, system velocity, emitting height, line width and so on) can be tuned to optimize the mask fit. However, even the best tuned masks include a small amount of contaminating flux at the expense of better capturing the HDO and  $\text{H}_2^{18}\text{O}$  flux. HDO 241 GHz has the largest amount of contamination from its neighbouring COM line, whereas  $\text{H}_2^{18}\text{O}$  also has some contamination. We show the channel maps of the HDO and  $\text{H}_2^{18}\text{O}$  emission with the Keplerian masks overlaid in Extended Data Figs. 1 and 2. The Keplerian masks for the contaminating lines are also drawn to show the expected velocities and location of the contaminating emission that overlap with the HDO and  $\text{H}_2^{18}\text{O}$  masks.

The Keplerian mask parameters used for each line are provided in Extended Data Table 2; we used consistent parameters between the Keplerian masks for the water lines and other COMs, different parameters were only necessary when the radial extent of emission was different or there were several hyperfine components to the transition, as in the case of  $\text{C}^{17}\text{O}$ . The exact same Keplerian mask parameters are used for the two HDO lines and the  $\text{H}_2^{18}\text{O}$  line for consistency in the analysis.

We then make use of these masks to extract moment maps of the emission and construct radial intensity profiles of the HDO and  $\text{H}_2^{18}\text{O}$  emission, using the `bettermoments` package<sup>38,39</sup>. In addition to the Keplerian masks, we also apply velocity range limits on the moment map calculations to omit unavoidable contaminating flux from neighbouring lines. As such, the 225 GHz HDO integrated intensity map includes velocities between 0.05 and 8.2 km s<sup>-1</sup> and the 241 GHz HDO and  $\text{H}_2^{18}\text{O}$  maps include velocities between 1.25 and 8.2 km s<sup>-1</sup>. Comparing with the HDO 225 GHz line, we find that the more limited ranges for HDO at 241 GHz and  $\text{H}_2^{18}\text{O}$  would only omit roughly 2% of the total line flux. The integrated intensity map for HDO at 241 GHz is shown in Extended Data Fig. 3.

The measured line fluxes within the Keplerian masks for HDO at 225 and 241 GHz are  $0.554 \pm 0.007$  and  $0.68 \pm 0.007$  Jy km s<sup>-1</sup>, respectively. Then the  $\text{H}_2^{18}\text{O}$  line flux was  $0.12 \pm 0.009$  Jy km s<sup>-1</sup>. The values for HDO 241 GHz and  $\text{H}_2^{18}\text{O}$  are larger than they should be because flux from contaminating spectral lines is present in overlapping velocity channels and falls within the Keplerian masks. If we only integrate the line flux in the velocity range from 5.05 to 7.05 km s<sup>-1</sup>, where contamination is minimal, we can scale to account for the missing flux by using the HDO 225 GHz line (ratio of the flux between 5.05 and 7.05 km s<sup>-1</sup> to the total line flux,  $0.37 \pm 0.008$ ). We measure a scaled HDO 241 GHz line flux of  $0.535 \pm 0.016$  Jy km s<sup>-1</sup> and a scaled  $\text{H}_2^{18}\text{O}$  line flux of  $0.093 \pm 0.014$  Jy km s<sup>-1</sup>. The scaled HDO 225 GHz line flux is identical to the

measurement from the full Keplerian mask value by definition. The line fluxes from the Keplerian masks in the full and 5.05 to 7.05 km s<sup>-1</sup> velocity ranges (scaled and unscaled) are provided in Extended Data Table 4.

We note that there is a small amount of contamination to the HDO 241 GHz line flux within the 5.05 to 7.05 km s<sup>-1</sup> velocity range. We correct for the estimated contamination to the HDO 241 GHz line flux in this velocity range by subtracting the estimated contamination, which is 2.3% of the total CH<sub>3</sub>CHO line flux (0.32 Jy km s<sup>-1</sup> estimated from spectral extraction, section Spectral extraction). The 5.05 to 7.05 km s<sup>-1</sup> spectral range for HDO 241 GHz corresponds to 7.33 to 9.33 km s<sup>-1</sup> from the line centre for CH<sub>3</sub>CHO. We then use the ratio of the total HDO 225 GHz line flux between 7.33 and 9.33 km s<sup>-1</sup> to the total HDO 225 GHz line flux to estimate that HDO at 241 GHz is contaminated by roughly 2.3% of the total CH<sub>3</sub>CHO line flux. This method of removing the estimated line flux only works because between 5.05 and 7.05 km s<sup>-1</sup> the CH<sub>3</sub>CHO Keplerian mask is wholly within the HDO 241 GHz Keplerian mask.

The uncertainties on the line fluxes are statistical only and do not include the estimated 5% absolute flux calibration uncertainty.

**Moment 0 extraction.** While the nearby COM spectral lines to the two HDO and H<sub>2</sub><sup>18</sup>O lines preclude a standard moment 0 map from accurately measuring the line fluxes, we can make use of a standard moment 0 map within the limited velocity range of 5.05 to 7.05 km s<sup>-1</sup>. This enables us to measure both the emission morphology and the significance of the line emission for the HDO and H<sub>2</sub><sup>18</sup>O lines without any potential bias caused by the pixel selections of the Keplerian masks. We show the moment 0 image computed between 5.05 and 7.05 km s<sup>-1</sup> in Extended Data Fig. 3 and overlay the contours of the H<sub>2</sub><sup>18</sup>O emission on the HDO emission to demonstrate the consistency of their emission morphologies.

We also measure the line fluxes directly from these moment 0 maps within a circle having a 0.4'' radius, centred on the continuum source. We measure line fluxes of  $0.244 \pm 0.007$ ,  $0.233 \pm 0.008$  and  $0.052 \pm 0.008$  for HDO 225 GHz, HDO 241 GHz and H<sub>2</sub><sup>18</sup>O, respectively. The HDO 241 GHz line flux is also corrected for the same amount of contamination from CH<sub>3</sub>CHO line flux between 5.05 and 7.05 km s<sup>-1</sup> as we did when the flux was measured within a Keplerian mask in the section on Keplerian masks. The line fluxes are also reported in Extended Data Table 4. We do notice that the line fluxes from the standard moment 0 extraction are systematically larger than those from the Keplerian masks in the same velocity range. The ratio of the Keplerian mask measured line fluxes between 5.05 and 7.05 km s<sup>-1</sup> to those from the moment 0 measurements are  $0.84 \pm 0.03$ ,  $0.88 \pm 0.03$  and  $0.65 \pm 0.14$  for HDO 225 GHz, HDO 241 GHz and H<sub>2</sub><sup>18</sup>O, respectively. This small discrepancy could result from the Keplerian mask excluding some line flux, but as we show later this does not lead to a significant difference in the measurement of the column densities of HDO and H<sub>2</sub><sup>18</sup>O nor the HDO:H<sub>2</sub>O ratio. Moreover, the scaled line fluxes from the moment 0 analysis are consistent within the 1 $\sigma$  uncertainties of the line fluxes from spectral extraction (Keplerian masks).

**Spectral extraction.** In addition to the analysis of the data cubes, we also perform an analysis of the disk-averaged spectra. We extract the spectra around the HDO, H<sub>2</sub><sup>18</sup>O, and methanol transitions within a 0.4'' radius circle centred on the continuum emission peak. The input data cubes are first converted from Jy beam<sup>-1</sup> to Jy pix<sup>-1</sup> and then all emission contained within the 0.4'' radius of the protostar position is summed, per channel, to create a one-dimensional spectrum. The spectra around the HDO and H<sub>2</sub><sup>18</sup>O lines are shown in Extended Data Fig. 4.

We also made use of spectral stacking, which removes the Keplerian kinematic pattern from the data and aligns the emitting components to be at the same velocity using the spectral-cube package<sup>40,41</sup>. This method boosts the signal to noise ratio of the spectral lines and makes the features sharper by lowering their velocity widths because

of the removal of the double-peaked line shape that is associated with Keplerian rotation. The spectrally stacked data make contaminating line features easier to identify and associate with the rest frequencies of molecular species. However, we do not perform measurements with the spectrally stacked data because a forward model using the spectral template is expected to be more reliable. Moreover, the spectral stacking can affect the line profiles in unexpected ways if not all emission lines come from the same emission layers within the disk or the midplane. Therefore, it is advantageous to use a spectral template to forward model the raw spectra. The stacked spectral data are presented in Extended Data Fig. 4 and clearly show that H<sub>2</sub><sup>18</sup>O is indeed detected with a peak at its expected frequency.

**Spectral fitting.** We constructed two different template spectra to disentangle the HDO and H<sub>2</sub><sup>18</sup>O from the contaminating lines. First, because the integrated intensity maps for methanol, HDO and H<sub>2</sub><sup>18</sup>O show that these molecules all have very similar spatial and velocity distributions, we used the isolated methanol lines that we detect in another spectral window as a spectral template for HDO, H<sub>2</sub><sup>18</sup>O and other COM lines in the disk. Second, we constructed a toy Keplerian disk model with a central protostar mass of 1.3 M<sub>⊙</sub> (ref. 6) using the Line Modelling Engine (LIME)<sup>42</sup> radiative transfer code to simulate the expected line profile of an optically thin molecule that is present in the disk between a radius of 20 and 85 AU. The model also excludes dust emission to make as ideal a spectrum as possible.

To construct the template spectrum using the methanol lines, we first extracted the five isolated methanol lines in our spectral window that targeted methanol at high spectral resolution (Extended Data Table 1), using the same aperture radius (0.4'') used to extract the other spectra. We then baseline subtracted the individual spectra to take out any slope in the spectral baseline. We next normalized each spectrum to have a maximum value of 1.0. Following normalization, we upsampled the spectral resolution of these lines by a factor of six and put all the individual methanol spectra on the same frequency axis. The spectra were averaged together to make a higher signal to noise template spectrum. We again baseline subtracted the new template spectrum to take out a residual slope in the spectral baselines. Finally, we mirrored the spectrum and averaged the mirror with itself to create a symmetric spectral profile. The mirroring creates a more idealized line profile for modelling emission lines other than methanol that may not have the exact same line shape.

To extract the one-dimensional spectrum from the LIME model, we use the same routines that we used to extract the spectra from the real data cubes and the 0.4'' extraction radius encompasses all the emission in the model. We also mirror this spectrum to smooth out any asymmetries that remain from the model gridding and noise in the radiative transfer calculations. The LIME and methanol template spectra are shown in Extended Data Fig. 5. The wings of the template lines agree well, and the primary difference is in the central portion of the line and to a lesser extent the location of the symmetric peaks. This difference is due to the high opacity of the methanol lines, which causes the centre of their line profiles to appear more filled-in relative to the peaks at higher and lower frequencies. These template spectra enable us to deblend the HDO and H<sub>2</sub><sup>18</sup>O lines from the COM lines without using the spectrally stacked data. Both spectral templates are resampled to the lower spectral resolution of the data for fitting.

The HDO lines were all brighter than the nearby contaminating COM lines, and each HDO line was blended with roughly two COM lines. Generally, a single line was the primary contaminating feature and there was tentative contamination from a second COM line. Then H<sub>2</sub><sup>18</sup>O had contamination primarily from one nearby COM line, but two other lines of the same species are also nearby. We list the most likely contaminating COM lines in Extended Data Table 3. The plausibility of the contaminating features relied on the positive identification of the species towards V883 Ori from previous work<sup>15</sup> and that the feature

could be present with a reasonable column density ( $10^{14}$ – $10^{16}$  cm $^{-2}$ ) and a temperature of 200–300 K, as simulated with the eXtended CASA Line Analysis Software Suite (XCLASS)<sup>43</sup>. Similar to previous work, we find that H<sub>2</sub><sup>18</sup>O has contamination from CH<sub>3</sub>OCH<sub>3</sub>, HDO 225 GHz has contamination from CH<sub>3</sub>OCHO (refs. <sup>21,22</sup>), but we also find that HDO at 225 GHz could be contaminated by <sup>13</sup>CH<sub>3</sub>CHO (an acetaldehyde isotopologue). Then, HDO at 241 GHz was found to be most probably contaminated by CH<sub>3</sub>CHO, with a possible second, weaker contaminating feature from (CH<sub>3</sub>)<sub>2</sub>CO (acetone).

With the frequencies of the contaminating lines identified, and the well-constrained velocity of the source (4.25 km s $^{-1}$ ) determined from the high spectral resolution methanol emission detected in our data set, we are able to model the spectral features of HDO and H<sub>2</sub><sup>18</sup>O and their surrounding lines with a linear addition of the scaled template spectra. We provided the rest frequencies for each line and used the scipy function minimize to find the best fitting multiplicative factors to fit the spectra using scaled spectral templates; rest frequencies of the spectral features were kept fixed. The results of the spectral fitting are shown in Extended Data Fig. 4.

We decided to adopt the optically thin spectral template for our fiducial model because it qualitatively fits the HDO spectra better than the methanol model. However, the subtle differences in the line fluxes whether we use the optically thin model, the methanol model, or the optically thin model for HDO and H<sub>2</sub><sup>18</sup>O and the methanol model for COMs does affect the excitation temperature, and hence the line column densities and HDO:H<sub>2</sub>O ratios. However, the HDO:H<sub>2</sub>O ratios are all consistent within their 1 $\sigma$  uncertainties, so the choice of model does not significantly affect the results as a whole.

The line fluxes were measured from the spectrum with the contaminating COM lines subtracted and uncertainties are derived from the root mean square of the residual spectrum with all fitted lines removed. This approach takes into account any uncertainties associated with imperfect fitting of the contaminating lines. We also tested Markov chain Monte Carlo methods to fit the spectra, but the results did not differ from the maximum likelihood fit using scipy’s minimize function. However, to validate our assumption of a fixed velocity and not allow the source velocity to be optimized, we randomly sampled velocities within 5% of 4.25 km s $^{-1}$  and determined whether the width of the distribution of fitted line flux densities was smaller or larger than the statistical uncertainty from the root mean square of the residuals. For all the water lines, the statistical uncertainty was smaller than the error in flux that could result from an imperfect system velocity. The line fluxes derived from the spectral template models are given in Extended Data Table 4.

The measurements of the line fluxes for all spectral template models are not entirely in agreement between the spectral fitting methods, Keplerian mask extraction methods and scaled moment 0 methods. Some differences can be explained by contamination of the HDO 241 GHz line in particular, but the largest differences are for the HDO 225 GHz line flux from the Keplerian mask and the scaled moment 0 line flux from the 5.05 to 7.05 km s $^{-1}$  moment 0 map. But, most flux differences are within 3 $\sigma$ , and the with HDO 241 GHz and H<sub>2</sub><sup>18</sup>O being consistent within 2 $\sigma$ . Some difference can be expected for several reasons. First, we integrate the spectra over the same circular aperture in all channels, whereas the Keplerian mask has more limited spatial extent because it only covers the portion of the disk expected to be emitting at a particular velocity. However, the projected outer extent of the Keplerian masks is comparable to 0.4'' spectral extraction radius. Second, the masks are also more limited in their spectral extents to avoid too much contamination from other lines, particularly for HDO at 241 GHz and H<sub>2</sub><sup>18</sup>O. Third, some true line emission can extend beyond the Keplerian mask at a given velocity channel and this would be specifically excluded from the Keplerian mask line flux, but included in the integrated spectrum. The most easily quantified difference is the difference in spectral range of the Keplerian mask, which results in just a 2% flux difference. The impact of these differences on the resultant

column densities are explored further in the section ‘HDO:H<sub>2</sub>O results from Keplerian mask and moment 0 line fluxes’.

**Measuring column densities.** We measure the column densities of HDO and H<sub>2</sub><sup>18</sup>O following standard methods under the assumption that the lines are optically thin and in local thermodynamic equilibrium (LTE)<sup>44</sup>. The spectral line parameters and partition functions were taken from the NASA Jet Propulsion Laboratory (JPL) database<sup>45</sup>. We first measure the line integrated intensities in units of Jy km s $^{-1}$ , which we then convert to temperature units through

$$\int T_B d\nu = \frac{c^2}{2\nu^2 k_B \Omega} \int F_\nu d\nu, \quad (1)$$

where  $k_B$  is the Boltzmann constant,  $T_B$  is the brightness temperature,  $F_\nu$  the flux density,  $\nu$  the frequency,  $c$  the speed of light,  $\Omega = \pi R^2$ , and  $R$  the 0.4'' aperture radius (converted to radians) used for extracting the spectra. The radial profiles are extracted from the data cubes in K km s $^{-1}$  using the bettermoments package<sup>38,39</sup>.

The column densities of the upper energy level are determined from the equation

$$N_u = \frac{8\pi k_B \nu_u^2}{hc^3 A_{ul}} \int T_B d\nu \quad (2)$$

where  $h$  is Planck’s constant,  $\nu$  is the frequency of the transition, and  $A_{ul}$  is the Einstein A coefficient for the transition. An estimate of the excitation temperature is then needed to determine total column densities, which we obtain from the ratio of column densities in the HDO 225 and 241 GHz lines through

$$T_{\text{ex}} = \frac{E_{u,225\text{GHz}} - E_{u,241\text{GHz}}}{\ln\left(\frac{N_{u,225\text{GHz}} g_{u,241\text{GHz}}}{N_{u,241\text{GHz}} g_{u,225\text{GHz}}}\right)} \quad (3)$$

where  $E_u$  is the upper level energy of the two HDO transitions in units of Kelvin and  $g_u$  is the statistical weight for each transition. Then the total column density for each transition is given by

$$N = \frac{N_u}{g_u} Q_{\text{rot}}(T_{\text{ex}}) e^{\frac{E_u}{T_{\text{ex}}}} \quad (4)$$

where  $Q_{\text{rot}}(T_{\text{ex}})$  is the partition function and  $T_{\text{ex}}$  is the excitation temperature. We use the tabulated partition functions from the JPL database as a function of temperature for HDO and H<sub>2</sub><sup>18</sup>O, and for  $T_{\text{ex}}$  values in between the tabulated temperatures we interpolate. Also, we use the full partition function for H<sub>2</sub><sup>18</sup>O that includes both the *ortho* and *para* states, implicitly correcting for the *ortho* to *para* ratio (OPR) of H<sub>2</sub><sup>18</sup>O. The calculated values for the interpolated partition functions are listed in Extended Data Table 4. The OPR for H<sub>2</sub><sup>18</sup>O is assumed to be three, substantial differences from this amount are not expected. The comet 67P was found to have an OPR of  $2.94 \pm 0.06$  (ref. <sup>46</sup>), which is consistent with the laboratory work finding that evaporating ices have an OPR of three<sup>47</sup>. We convert the H<sub>2</sub><sup>18</sup>O column density to an H<sub>2</sub>O column density by multiplying by the <sup>16</sup>O:<sup>18</sup>O ratio of  $560 \pm 25$  (ref. <sup>48</sup>). However, we do know that the <sup>16</sup>O:<sup>18</sup>O in 67P for H<sub>2</sub>O is  $445 \pm 35$  (ref. <sup>49</sup>). Therefore, it is possible that the actual H<sub>2</sub>O column densities in V883 Ori are lower, which would further elevate the HDO:H<sub>2</sub>O ratio.

The uncertainties in the column densities and ratios are derived from standard error propagation. The uncertainty on the HDO column densities includes the random measurement error from the noise in each channel, the roughly 5% absolute flux density calibration uncertainty (only included once in the average HDO column density as both lines are observed simultaneously), and the uncertainty in the excitation temperature. The H<sub>2</sub><sup>18</sup>O also includes the further uncertainty on the



# Article

ratio of  $^{16}\text{O}$  to  $^{18}\text{O}$  (neglecting the possibility of a large systematic uncertainty). These uncertainties are all propagated into the HDO:H<sub>2</sub>O ratio such that the uncertainties on our derived ratio include all the known uncertainties and better reflect the absolute accuracy of the measurement versus only including statistical measurement uncertainties. Finally, we did not make a correction for extra dust attenuation of the 225 and 241 GHz HDO lines relative to H<sub>2</sub><sup>18</sup>O at 203 GHz when calculating the HDO:H<sub>2</sub>O ratio. This correction would have a radial dependence and would depend on the adopted power-law dust opacity dependence with frequency. The application of such a correction would only result in a higher HDO column density and a higher HDO:H<sub>2</sub>O ratio as dust attenuation is larger at higher frequencies.

We further note that the excitation temperature derived is not expected to be very accurate because of the small range of upper level energies sampled by the HDO lines (95 and 167 K), but the HDO:H<sub>2</sub>O ratio only varies by a factor of roughly 2 for temperatures between 75 and 225 K, so the precision of the excitation temperature is not extremely important.

The assumption of LTE is appropriate for the V883 Ori disk. The critical densities of the HDO 225, 241, and H<sub>2</sub><sup>18</sup>O 203 GHz are  $9.72 \times 10^5$ ,  $1.06 \times 10^6$  and  $3.79 \times 10^5 \text{ cm}^{-3}$ , respectively, using the collision coefficients for a temperature of roughly 200 K from the Leiden Atomic and Molecular Database (coefficients for *para*-H<sub>2</sub>O are used for *para*-H<sub>2</sub><sup>18</sup>O)<sup>50,51</sup>. These critical densities are satisfied even for protostars in which the origin of the emission is likely to have contributions from the envelope outside the disk. Moreover, previous analyses have examined the difference between LTE and radiative transfer models that take into account non-LTE effects<sup>21,22</sup>. Those studies find that the HDO:H<sub>2</sub>O ratios derived from non-LTE modelling are consistent with the LTE calculations or differ by factors of only 3 to 4. Also, they often indicate even higher HDO:H<sub>2</sub>O ratios and are thus not regarded as being more accurate. Finally, a simple estimate of the disk density in the upper layers at a height of 50 AU and a radius of 80 AU we find that the density would be roughly  $7.4 \times 10^6 \text{ cm}^{-3}$ . All other emission would be from lower layers at higher density and also fulfilling the conditions for LTE. We estimated the disk density by assuming parameters typical for an irradiated disk using a parameterized surface and vertical density profile<sup>52</sup>

$$\rho(r, z) = \frac{\Sigma(r)}{\sqrt{2\pi}H(r)} \exp\left(-\frac{z^2}{2H(r)^2}\right). \quad (5)$$

where  $r$  is the cylindrical radius,  $z$  is the height above the midplane, and  $\Sigma(r)$  is

$$\Sigma(r) = \Sigma_0 \left(\frac{r}{10 \text{ AU}}\right)^{-1} \quad (6)$$

and  $\Sigma_0 = 100 \text{ g cm}^{-2}$ , as is typical for a roughly  $0.01 M_{\odot}$  proto-planetary disk<sup>17</sup>, chosen as a conservative lower limit.  $H(r)$  for the gas disk is parameterized as

$$H = 1.0 \text{ AU} \left(\frac{r}{10 \text{ AU}}\right)^{1.25} \quad (7)$$

which is typical for an irradiated disk.

## HDO:H<sub>2</sub>O results from Keplerian mask and moment 0 line fluxes.

We noted earlier that the line fluxes extracted using a Keplerian mask and integrated intensity maps from 5.05 to 7.05 km s<sup>-1</sup> differed from those derived from the spectrum and it is worthwhile examining how line flux extraction using the Keplerian mask would affect our results. Note that we correct for the 2% reductions to the HDO 241 GHz and H<sub>2</sub><sup>18</sup>O line fluxes due to the smaller channel ranges used relative to HDO 225 GHz in their line flux measurements in the calculations that follow. The values for the line fluxes used to calculate the column densities

mentioned in the text below are also provided in Extended Data Table 4, in addition to the HDO:H<sub>2</sub>O ratios.

We examined line flux measurements that used the full Keplerian mask, which includes some unavoidable contamination from COMs in the 241 GHz and H<sub>2</sub><sup>18</sup>O channel maps. The contamination is difficult to avoid when using an identical Keplerian mask to the HDO 225 GHz line. Because of the contaminated line fluxes to the HDO 241 GHz line, the lower excitation HDO transition (Extended Data Table 3), the excitation temperature is found to be lowest for the full Keplerian mask measurement at  $112 \pm 3 \text{ K}$ . Then the HDO and H<sub>2</sub><sup>18</sup>O column densities are measured to be  $(5.07 \pm 0.26) \times 10^{15}$  and  $(4.75 \pm 0.44) \times 10^{15} \text{ cm}^{-2}$ , respectively. These measurements are both lower than those from the spectral extraction, but are consistent at the 1.4 and 0.5 $\sigma$  levels, respectively. The inferred H<sub>2</sub>O column density is  $(2.66 \pm 0.28) \times 10^{18} \text{ cm}^{-2}$ , which is corrected for the  $^{16}\text{O}$ : $^{18}\text{O}$  ratio and the OPR of three. The HDO and H<sub>2</sub>O column densities then yield a HDO:H<sub>2</sub>O ratio of  $(1.91 \pm 0.22) \times 10^{-3}$ , which is consistent with the value from spectral extraction within the uncertainties.

Because of the known significant contamination to HDO 241 GHz and H<sub>2</sub><sup>18</sup>O using the same Keplerian mask as HDO 225 GHz, without further optimization, we also examined the measurements obtained by integrating the flux density within a mostly contamination free region of the data cube (5.05 to 7.05 km s<sup>-1</sup>) and scaling the line flux from that spectral range to the expected flux from the full spectral range using the ratio of HDO 225 GHz flux integrated within a Keplerian mask to the HDO 225 GHz flux present between 5.05 and 7.05 km s<sup>-1</sup> ( $0.37 \pm 0.008$ ), also within a Keplerian mask. The HDO:H<sub>2</sub>O ratio remains unchanged whether we only compare line fluxes between 5.05 and 7.05 km s<sup>-1</sup> or scale to the expected full line flux, but to compare the column densities consistently, we need to make use of the scaled line fluxes.

The HDO, H<sub>2</sub><sup>18</sup>O, and inferred H<sub>2</sub>O column densities derived from scaled line fluxes measured within a Keplerian mask from 5.05 to 7.05 km s<sup>-1</sup> are  $(5.36 \pm 0.35) \times 10^{15}$ ,  $(3.76 \pm 0.58) \times 10^{15}$  and  $(2.11 \pm 0.34) \times 10^{18} \text{ cm}^{-2}$ , respectively, using the calculated excitation temperature of  $162 \pm 11 \text{ K}$ . These measurements are both lower than those from the spectral extraction, but are consistent at the 1.1 and 1 $\sigma$  levels, respectively. The HDO and H<sub>2</sub>O column densities then yield a HDO:H<sub>2</sub>O ratio of  $(2.54 \pm 0.44) \times 10^{-3}$ , which is consistent within the uncertainties with the value from spectral extraction.

Then, if we instead derive the column densities using the line fluxes measured from the standard moment 0 image computed between 5.05 and 7.05 km s<sup>-1</sup>, we measure HDO, H<sub>2</sub><sup>18</sup>O and inferred H<sub>2</sub>O column densities of  $(6.78 \pm 0.62) \times 10^{15}$ ,  $(5.92 \pm 1.00) \times 10^{15}$ ,  $(3.31 \pm 0.59) \times 10^{18} \text{ cm}^{-2}$  and, respectively, using the calculated excitation temperature of  $182 \pm 19 \text{ K}$ . These values are consistent with the values from spectral extraction within the uncertainties. The HDO and H<sub>2</sub>O column densities then yield a HDO:H<sub>2</sub>O ratio of  $(2.05 \pm 0.41) \times 10^{-3}$ , which is consistent within the uncertainties with the value from spectral extraction.

The high degree of consistency of the methods of spectral extraction, standard Keplerian mask, Keplerian mask between 5.05 and 7.05 km s<sup>-1</sup> and a standard moment 0 between 5.05 and 7.05 km s<sup>-1</sup> indicates that several methods arrive at compatible measurements for the HDO and H<sub>2</sub><sup>18</sup>O column densities and consistent measurements of the HDO:H<sub>2</sub>O ratio. Although the line contamination present in the case of the standard Keplerian mask of the full velocity range is not ideal, it also does not significantly alter the main result. Thus, we conclude that the method of line flux measurement does not significantly affect our results on the column densities and HDO:H<sub>2</sub>O ratio measured. The Keplerian mask and standard moment 0 measurements do, however, tend to have lower uncertainties because they make use of measurements over smaller ranges of velocity and/or a smaller number of pixels (through the mask), which reduces the noise that is added from the summation of several channels. We still favour the spectral analysis method because this makes use of the full spectral range of the data rather than subsets of the full data set.

## Birth environment of V883 Ori relative to the Sun and other protostars

V883 Ori is compared with Class 0 protostars, comets and water in Earth's oceans in Fig. 4 attempting to determine whether there is an evolutionary sequence in the HDO:H<sub>2</sub>O ratios. However, we already know that V883 Ori has formed in a different environment compared to the Sun/Solar System and other Class 0 protostars. V883 Ori is forming within the Orion A giant molecular cloud and is roughly 10 pc from the main cluster/nebula and the nearest protostar is roughly 0.4 pc away: both measurements are in projected distances, thus it is relatively isolated within Orion. By contrast, the Class 0 protostars with measured HDO:H<sub>2</sub>O ratios come from a mix of isolated and protostars within small clusters<sup>22</sup> and the isolated Class 0 protostars have systematically higher HDO:H<sub>2</sub>O ratios. V883 Ori's HDO:H<sub>2</sub>O ratio is most similar to the isolated Class 0 protostars. This may make sense because it is relatively isolated itself, but the isolated protostars are forming in truly isolated cores and are not part of a larger molecular cloud, unlike V883 Ori. It is still unknown what causes the higher HDO:H<sub>2</sub>O ratios for isolated systems, but it remains to be seen whether the difference between isolated and clustered protostars remains with larger samples.

The Sun and Solar System were probably formed in a cluster within a giant molecular cloud, which could have been similar to Orion<sup>53,54</sup>. However, the dynamical constraints that are available for the evolution of the Solar System point to its formation environment being closer to, or within the main cluster<sup>55</sup>. Thus, V883 Ori is not forming in completely analogous conditions relative to the early Solar System. Nonetheless, it is still extremely relevant to compare the measurements for V883 Ori to comets within the Solar System and Earth given that they represent the only available measurements of more-evolved bodies. Furthermore, if water is inherited relatively unchanged from the cold molecular cloud phase, the fact that both the Sun/Solar System and V883 Ori formed within giant molecular clouds suggests that it is reasonable to compare the HDO:H<sub>2</sub>O ratios of these systems.

## Measurements of deuterium to hydrogen ratios from the literature

To create Fig. 4, we collected various published measurements for protostars and comets from the literature. We have assembled these measurements in Extended Data Table 5 for reference.

## Data availability

The images used for analysis in the paper are available in the Harvard Dataverse repository (<https://doi.org/10.7910/DVN/MDQJEU>), along with the reduction scripts used to process the ALMA visibility data and create images. Owing to their size, the raw (and ALMA-pipeline-calibrated) visibility data are only available from the ALMA science archive (<https://almascience.nrao.edu/aq/>).

## Code availability

Codes used for analysis are available in the Harvard Dataverse repository (<https://doi.org/10.7910/DVN/MDQJEU>), along with the ALMA images used for analysis. Documentation and requirements for various parts of the code are documented.

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# Article

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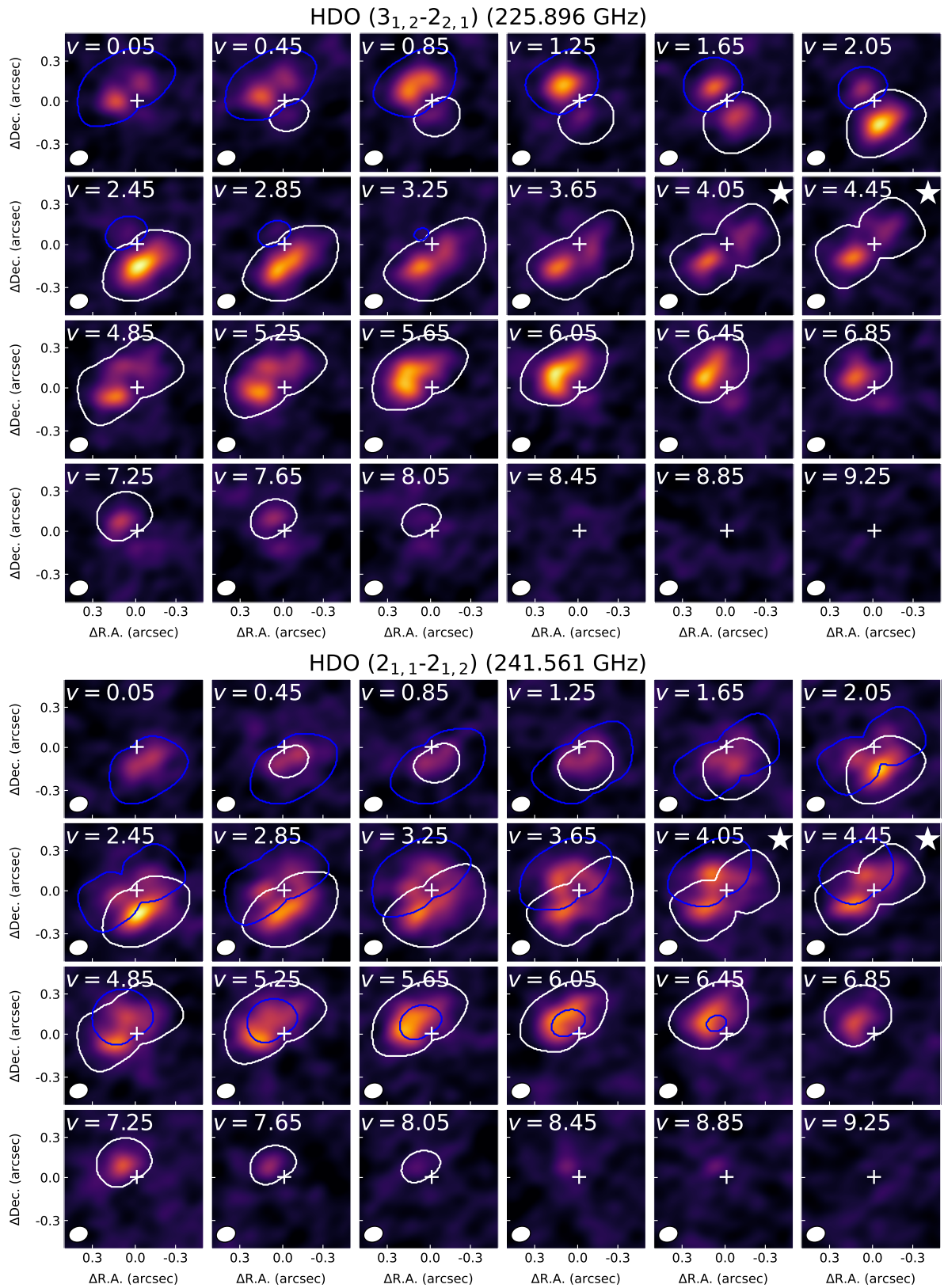
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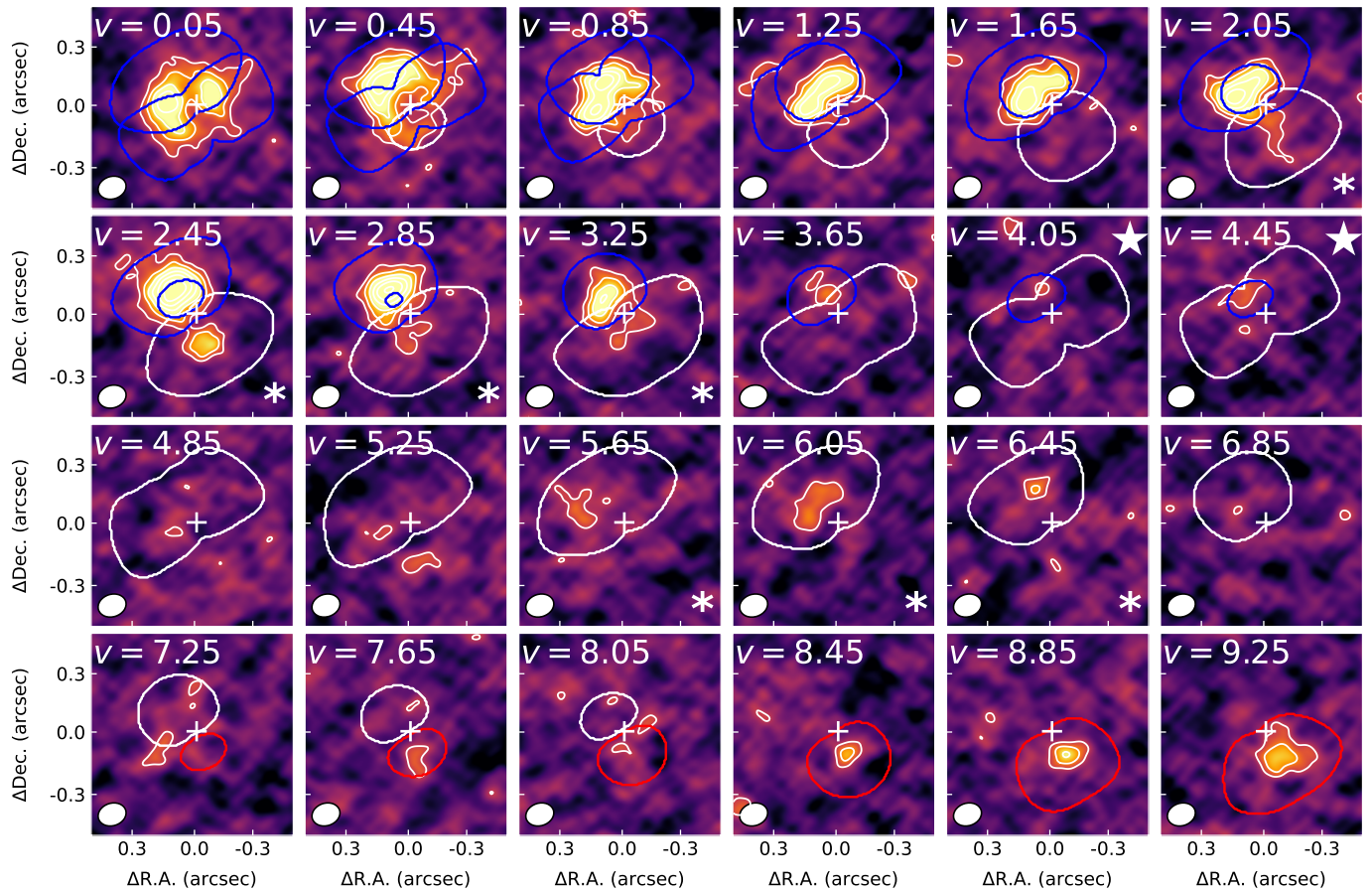
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**Extended Data Fig. 1 | Channel maps of HDO 225 and 241 GHz emission.** The data are shown by the colour scale, the Keplerian mask is drawn as a heavy white line, and the mask corresponding to the blueshifted  $\text{CH}_3\text{OCHO}$  line (Extended Data Fig. 4) is drawn as a heavy blue line for HDO 225 GHz and  $\text{CH}_3\text{CHO}$  for HDO

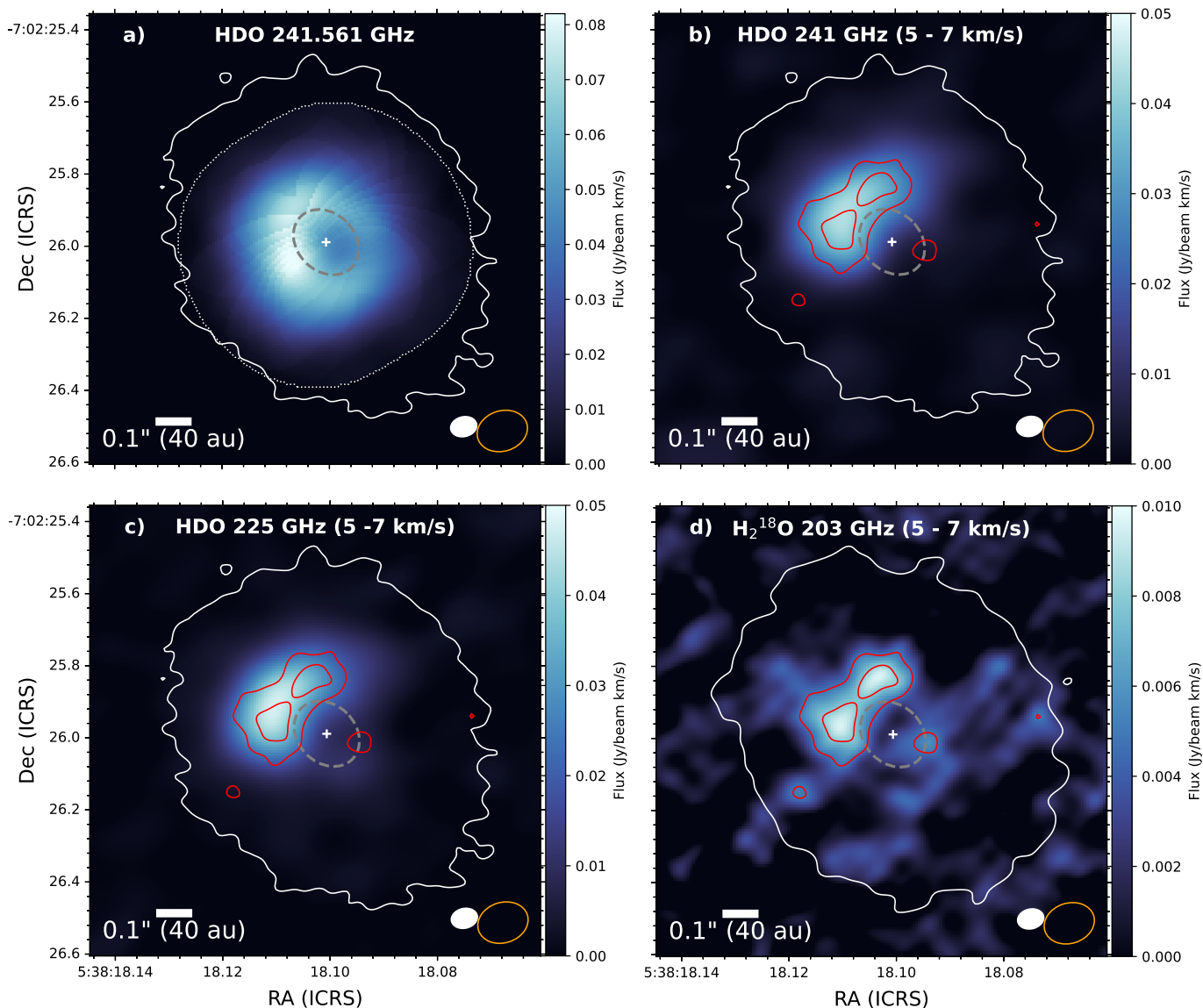
241 GHz. The continuum peak/protostar position is marked by the white cross. The channels nearest the velocity of V883 Ori ( $4.25 \text{ km s}^{-1}$ ) are marked with a star in the upper right corner. The synthesized beam is also drawn in the lower left corner of each panel.



$\text{H}_2^{18}\text{O}$  ( $3_{1,3}-2_{2,0}$ ) (203.407 GHz)

**Extended Data Fig. 2 | Channel maps of  $\text{H}_2^{18}\text{O}$  203 GHz emission.** The data are shown by the colour scale, the Keplerian mask for  $\text{H}_2^{18}\text{O}$  is drawn as a heavy white line, and the masks corresponding to the two blueshifted and one redshifted  $\text{CH}_3\text{OCH}_3$  lines (Extended Data Fig. 4) are drawn as heavy blue and red lines, respectively. The continuum peak/protostar position is marked by the white cross and the channels nearest the velocity of V883 Ori ( $4.25 \text{ km s}^{-1}$ )

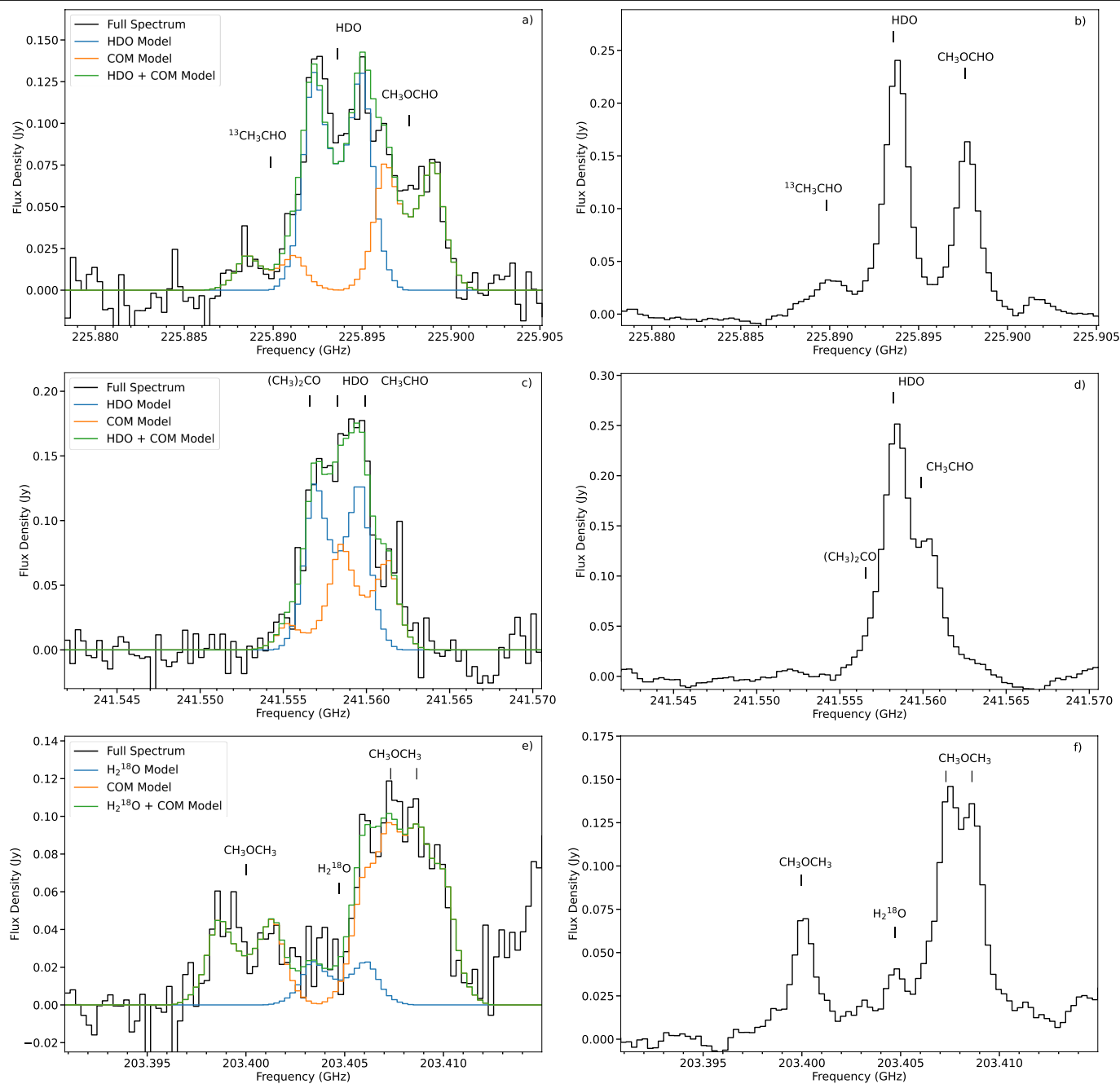
are marked with a star in the upper right corner. Despite the faintness of the  $\text{H}_2^{18}\text{O}$  line and its location between nearby COM lines, the detection of  $\text{H}_2^{18}\text{O}$  is unambiguous given that its emission is detected in the expected channels for the given protostar mass. The channels with  $>3\sigma$  detections within the Keplerian masks are marked with asterisks in the lower right corner. The synthesized beam is drawn in the lower left corner of each panel.



**Extended Data Fig. 3 | Integrated intensity images of HDO and H<sub>2</sub><sup>18</sup>O.** The HDO 241 GHz integrated intensity map created using a Keplerian mask identical to the HDO 225 GHz and H<sub>2</sub><sup>18</sup>O lines is shown in **a**, the HDO 241 GHz integrated intensity image between 5.05 and 7.05 km s<sup>-1</sup> is shown in **b**, the HDO 225 GHz integrated intensity image using the same velocity range is shown in **c**, and the H<sub>2</sub><sup>18</sup>O integrated intensity image from the same velocity range is shown in **d**. The contours shown in **b–d** are from the H<sub>2</sub><sup>18</sup>O image and show the intensity levels 3 and 5 times the noise (s.d.), where 1 s.d. is 0.00158 Jy beam<sup>-1</sup> km s<sup>-1</sup>, and the integrated intensity images in these panels were computed without the use of masks or any other clipping. The 5.05 to 7.05 km s<sup>-1</sup> velocity range had minimal contamination from other lines for HDO and H<sub>2</sub><sup>18</sup>O and effectively

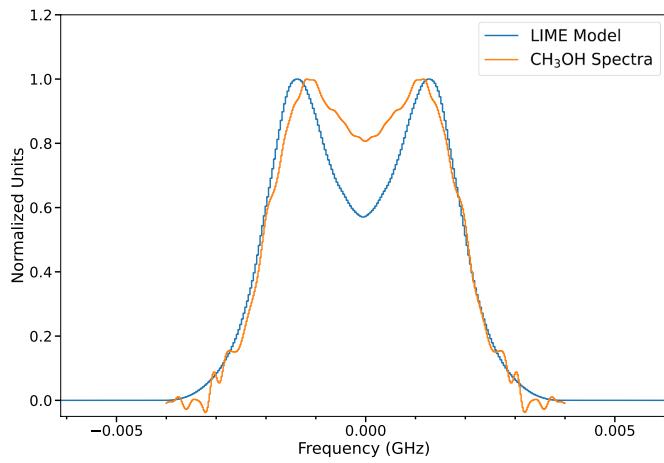
demonstrates the significance of the H<sub>2</sub><sup>18</sup>O detection. The extent of the continuum emission from the disk is denoted by the white contour and the position of the protostar is marked with the white cross. The HDO 241 GHz line shows very similar structure to the HDO 225 GHz line that is shown in Fig. 2 in the main text, and the dotted line in **a** shows the region over which the integrated intensity image was computed using the Keplerian mask. The depression in the centre of the line emission in **a** is the result of optically thick continuum absorbing the line emission in the inner ~0.1" (40 au). The extent of this optically thick region is denoted with the thick grey line in the centre of each image. The ellipses in the lower right corner denote the resolution of the line observation (orange, ~0.1") and the continuum data (white, ~0.08").





**Extended Data Fig. 4 | Integrated spectra of V883 Ori centered on the HDO 225 GHz, HDO 241 GHz, and  $\text{H}_2^{18}\text{O}$  203 GHz lines.** Panels a, c, e show the spectra as observed (disk rotation causes all spectral lines to have a double-peaked line profile), while panels b, d, f show the stacked spectra<sup>40,41</sup> with the Keplerian rotation profile removed. The root mean squared (RMS) noise of the HDO 225 GHz, HDO 241 GHz, and  $\text{H}_2^{18}\text{O}$  are 0.016, 0.017, and 0.011 Jy, respectively. The HDO lines are the brightest features around their centre frequencies, but both have contaminating emission from COM species nearby. The  $\text{H}_2^{18}\text{O}$  line is faint relative to its surrounding features but is still clearly detected. We are able to model the spectral profiles for HDO,  $\text{H}_2^{18}\text{O}$ , and the

contaminating lines to measure their line fluxes using an optically-thin synthetic spectral model for a disk (Extended Data Fig. 5). In a, c, e, the observed spectrum is drawn as the black line, the model of the contaminating lines is drawn as an orange line, the model HDO and  $\text{H}_2^{18}\text{O}$  lines are drawn as blue lines, and the total model of contaminating lines with HDO and  $\text{H}_2^{18}\text{O}$  is drawn as a green line. The rise seen toward higher frequencies on the  $\text{H}_2^{18}\text{O}$  spectrum (e) is another  $\text{CH}_3\text{OCH}_3$  line that peaks outside the shown region. The spectra are plotted at their observed frequencies and are not corrected for the system local standard of rest (LSR) velocity of  $\sim 4.25 \text{ km s}^{-1}$ .



**Extended Data Fig. 5 | Plot of template spectra derived from the LIME radiative transfer model and from the observed isolated methanol lines.** The main difference between the templates is at the centre of the line profile where the methanol line has a much more shallow dip owing to line optical depth, while the optically thin LIME model has a much deeper dip at the centre and sharper peaks.

# Article

## Extended Data Table 1 | Spectral setup

Line	Rest Frequency (GHz)	Band Width (MHz)	Spectral Resolution (KHz, km s <sup>-1</sup> )	Beam (")
<b>Band 5 Data</b>				
H <sub>2</sub> <sup>18</sup> O 3(1,3)- 2(2,0)	203.40752	234.375	122.070, 0.18	0.142 × 0.112
CH <sub>3</sub> CN <sup>a</sup>	202.351612	234.375	122.070, 0.18	0.143 × 0.113
Continuum	190.5	1875	1129, 1.777	0.150 × 0.122
Continuum	188.7	1875	1129, 1.794	0.151 × 0.121
<b>Band 6 Data</b>				
H <sub>2</sub> CO 3(1,2)-2(1,1)	225.697775	58.594	122.070, 0.162	0.105 × 0.083
CH <sub>3</sub> OD 5(0,5)-4(0,4) A	226.538674	58.594	122.070, 0.162	0.105 × 0.083
C <sup>17</sup> O J=2-1	224.714373	58.594	122.070, 0.162	0.106 × 0.083
HDO 3(1,2)-2(2,1)	225.89672	58.594	122.070, 0.162	0.104 × 0.082
CN <sup>a</sup>	226.6595584	117.188	141.113, 0.187	0.102 × 0.081
CN <sup>a</sup>	226.87478	117.188	141.113, 0.186	0.102 × 0.081
Continuum	240.5	1875	1129, 1.407	0.099 × 0.078
HDO 2(1,1)-2(1,2)	241.56155	117.188	122.070, 0.152	0.098 × 0.077
CH <sub>3</sub> OH <sup>a</sup>	241.83165	117.188	122.070, 0.151	0.098 × 0.078
CH <sub>3</sub> OH <sup>b</sup> 5(4)- 4(4)-	241.806524	"	"	"
CH <sub>3</sub> OH <sup>b</sup> 5(-4) - 4(-4) E2	241.813255	"	"	"
CH <sub>3</sub> OH <sup>b</sup> 5(-3) - 4(-3) E2	241.852299	"	"	"
CH <sub>3</sub> OH <sup>b</sup> 5(1) - 4(1) E1	241.879025	"	"	"
CH <sub>3</sub> OH <sup>b</sup> 5(2)+ - 4(2)+	241.887674	"	"	"

Note: while spectral windows are identified as targeting a particular line or continuum, they also generally contain spectral features from other molecules.

<sup>a</sup>Several features of this molecule are contained within the spectral window.

<sup>b</sup>Methanol lines that were isolated enough to use for creation of a template spectrum.

## Extended Data Table 2 | Keplerian mask parameters

Datacube	Line	$V_{\text{sys}}$ ( $\text{km s}^{-1}$ )	Smoothing (Frac. Beam)	$R_{\text{max}}$ (arcsec)	Z/R	$\Delta V$ ( $\text{km s}^{-1}$ )
HDO 225 GHz	HDO 3(1,2)-2(2,1)	4.25	1.25	0.3	0.4	0.35
	CH <sub>3</sub> OCHO 225.90074 GHz	-1.09 <sup>b</sup>	1.25	0.3	0.4	0.35
HDO 241 GHz	HDO 2(1,1)-2(1,2)	4.25	0.5	0.3	0.2	0.35
	CH <sub>3</sub> CHO 241.5632277 GHz	2.17 <sup>b</sup>	0.5	0.3	0.2	0.35
H <sub>2</sub> CO	H <sub>2</sub> CO 3(1,2)-2(1,1)	4.25	1.75	0.9	0.2	1.0
C <sup>17</sup> O	C <sup>17</sup> O (J=2-1) <sup>a</sup>	3.7	1.25	0.85	0.2	1.2
	C <sup>17</sup> O (J=2-1) <sup>a</sup>	4.6	1.25	0.85	0.2	1.2
CH <sub>3</sub> OH	241.887674 GHz	-50.4 <sup>b</sup>	1.75	0.4	0.4	0.35
	241.879025 GHz	-39.7 <sup>b</sup>	1.75	0.4	0.4	0.35
	241.852299 GHz	-6.5 <sup>b</sup>	1.75	0.4	0.4	0.35
	241.813255 GHz	41.9 <sup>b</sup>	1.75	0.4	0.4	0.35
	241.806524 GHz	50.3 <sup>b</sup>	1.75	0.4	0.4	0.35
H <sub>2</sub> <sup>18</sup> O	H <sub>2</sub> <sup>18</sup> O 3(1,3)- 2(2,0)	4.25	1.25	0.3	0.4	0.35

Note: All masks assumed a stellar mass of  $1.285 M_{\odot}$ , an inclination of  $38.3^{\circ}$ , a position angle of  $32^{\circ}$ , a distance of 400 pc, and an inner radius of  $0.1''$ .

H<sub>2</sub>CO and C<sup>17</sup>O both used an inner radius of  $0.05''$ .

<sup>a</sup>RMS noise of a line-free region of the spectrum.

<sup>b</sup>Offset velocity from the rest frequency of the cube, adopted source velocity was  $4.25 \text{ km s}^{-1}$ .

# Article

**Extended Data Table 3 | Spectral lines blended with HDO and H<sub>2</sub><sup>18</sup>O**

Molecule	Transition	Rest Frequency (GHz)	Upper Level Energy (K)	Einstein A (log <sub>10</sub> (s <sup>-1</sup> ))	RMS <sup>a</sup> (Jy)
H <sub>2</sub> <sup>18</sup> O					0.011
H <sub>2</sub> <sup>18</sup> O	3(1,3)-2(2,0)	203.40752	203.7	-5.31770	
CH <sub>3</sub> OCH <sub>3</sub>	3(3,1)-2(2,1) EE	203.4101126	18.1	-4.26493	
CH <sub>3</sub> OCH <sub>3</sub>	3(3,0)-2(2,1) AE	203.4114309	18.1	-4.02956	
CH <sub>3</sub> OCH <sub>3</sub>	3(3,1)-2(2,1) EA	203.4027779	18.1	-4.18698	
HDO 225 GHz					0.016
HDO	3(1,2)-2(2,1)	225.89672	167.6	-4.87987	
CH <sub>3</sub> OCHO	6(6,0)-5(5,0) E	225.90074	36.3	-4.58474	
<sup>13</sup> CH <sub>3</sub> CHO <sup>b</sup>	12(2,10) - 11(2,9) E, vt=1	225.8929484	285.7	-3.40579	
HDO 241 GHz					0.017
HDO	2(1,1)-2(1,2)	241.56155	95.2	-4.92559	
CH <sub>3</sub> CHO	21(2,19)-20(3,18) E	241.5632277	226.4	-4.70342	
(CH <sub>3</sub> ) <sub>2</sub> CO	13(10,4)-12(9,3) AA	241.5598869	77.7	-3.48114	

<sup>a</sup>RMS noise of a line-free region of the spectrum.

<sup>b</sup>Tentatively identified line.

**Extended Data Table 4 | Impact of different spectral models on line flux**

Model	Temp. (K)	Q(T) <sup>a</sup> (HDO, H <sub>2</sub> <sup>18</sup> O)	HDO/H <sub>2</sub> O	HDO(225) (Jy km s <sup>-1</sup> )	HDO(241) (Jy km s <sup>-1</sup> )	H <sub>2</sub> <sup>18</sup> O (Jy km s <sup>-1</sup> )
Optically-thin	199 ± 42	80.6, 98.8	(2.26 ± 0.63) × 10 <sup>-3</sup>	0.644 ± 0.028	0.595 ± 0.037	0.126 ± 0.025
Methanol	210 ± 48	86.7, 106.2	(1.85 ± 0.51) × 10 <sup>-3</sup>	0.64 ± 0.024	0.581 ± 0.04	0.155 ± 0.025
Both <sup>b</sup>	276 ± 87	130.6, 159.8	(1.92 ± 0.49) × 10 <sup>-3</sup>	0.653 ± 0.026	0.546 ± 0.040	0.159 ± 0.024
Keplerian Mask <sup>c</sup>	112 ± 3	35.2, 43.3	(1.91 ± 0.22) × 10 <sup>-3</sup>	0.554 ± 0.007	0.680 ± 0.007	0.111 ± 0.009
5.05 to 7.05 km s <sup>-1</sup> d						
Keplerian Mask <sup>e</sup>	162 ± 10	59.5, 73.0	(2.54 ± 0.44) × 10 <sup>-3</sup>	0.205 ± 0.004	0.206 ± 0.004	0.034 ± 0.005
Keplerian Mask (scaled) <sup>f</sup>	162 ± 10	59.5, 73.0	(2.54 ± 0.44) × 10 <sup>-3</sup>	0.554 ± 0.007	0.555 ± 0.016	0.093 ± 0.014
Moment 0 <sup>g</sup>	182 ± 19	70.7, 86.6	(2.05 ± 0.41) × 10 <sup>-3</sup>	0.244 ± 0.007	0.233 ± 0.008	0.052 ± 0.008
Moment 0 (scaled) <sup>h</sup>	182 ± 19	70.7, 86.6	(2.05 ± 0.41) × 10 <sup>-3</sup>	0.658 ± 0.018	0.63 ± 0.020	0.14 ± 0.023

<sup>a</sup>Calculated value of the partition function at the listed temperature.

<sup>b</sup>The optically thin model is used for the HDO and H<sub>2</sub><sup>18</sup>O lines while the methanol model is used for the COM lines.

<sup>c</sup>Line fluxes measured straight from Keplerian masks, without fine-tuned masks to avoid contamination for H<sub>2</sub><sup>18</sup>O or HDO 241 GHz. As such, the HDO 241 GHz and H<sub>2</sub><sup>18</sup>O line fluxes are overestimated and the excitation temperature is underestimated.

<sup>d</sup>Measurements are based line flux measurements only within 5.05 to 7.05 km s<sup>-1</sup>.

<sup>e</sup>HDO(241) has its flux reduced by 0.007 Jy km s<sup>-1</sup> to account for minor contamination from CH<sub>3</sub>CHO in its Keplerian mask.

<sup>f</sup>The ratio of HDO (225) line flux from 5.05 to 7.05 km s<sup>-1</sup> to its total line flux (0.37 ± 0.008) is used to scale the HDO(241) and H<sub>2</sub><sup>18</sup>O line fluxes to their expected values for the full velocity range.

<sup>g</sup>Line fluxes are summed in a 0.4" radius aperture.

<sup>h</sup>Line fluxes are summed in a 0.4" radius aperture, and scaled using the ratio of HDO (225) line flux from 5.05 to 7.05 km s<sup>-1</sup> to its total line flux (0.37 ± 0.008) from the Keplerian Mask measurement.



# Article

## Extended Data Table 5 | D/H measurements

Object	HDO/H <sub>2</sub> O	Method	Reference
<b>Earth</b>			
Earth's Oceans	$(3.11 \pm 0.002) \times 10^{-4}$	VSMOW	[60, 61]
<b>Oort Cloud comets</b>			
1/P Halley	$(4.20 \pm 0.6) \times 10^{-4}$	H <sub>2</sub> DO <sup>+</sup> /H <sub>3</sub> O <sup>+</sup>	[62]
C/1996 B2 Hyatuake	$(5.80 \pm 2.0) \times 10^{-4}$	HDO/H <sub>2</sub> O	[63]
C/1995 O1 Hale-Bopp	$(6.60 \pm 1.6) \times 10^{-4}$	HDO/H <sub>2</sub> O	[64]
C/2007 B3 Lulin	$< 1.12 \times 10^{-3}$	HDO/H <sub>2</sub> O	[65]
8P/Tuttle	$(8.20 \pm 3.0) \times 10^{-4}$	HDO/H <sub>2</sub> O	[66]
C/2009 P1 Garradd	$(4.12 \pm 0.44) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[67]
C/2002 T7 LINEAR	$(5.00 \pm 1.4) \times 10^{-4}$	OD/OH (H <sub>2</sub> <sup>18</sup> O)	[68]
153P Ikeya-Zhang	$(5.60 \pm 0.6) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[69]
C/2012 F6 Lemmon	$(6.50 \pm 1.6) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[70]
C/2014 Q2 Lovejoy	$(1.40 \pm 0.4) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[70]
<b>Jupiter Family comets</b>			
45P Honda-Mrkos-Pajdusakov (HMP)	$< 4.00 \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[71]
103P Hartley 2	$(3.20 \pm 0.5) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[72]
67P Churyumov-Gerasimenko	$(1.06 \pm 0.14) \times 10^{-3}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[24, 26]
46P/Wirtanen	$(3.20 \pm 1.3) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[73]
<b>Flat Spectrum Disk</b>			
V883 Ori	$(2.26 \pm 0.63) \times 10^{-3}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	This work
<b>Clustered Class 0 Protostars</b>			
NGC1333 IRAS 4A-NW	$(5.40 \pm 1.5) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[21]
NGC1333 IRAS 2A	$(7.40 \pm 2.1) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[21]
NGC1333 IRAS 4B	$(5.90 \pm 2.6) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[21]
IRAS 16293-2422	$(9.20 \pm 2.6) \times 10^{-4}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[21]
<b>Isolated Class 0 Protostars</b>			
BHR71 IRS	$(1.80 \pm 0.4) \times 10^{-3}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[22]
B335	$(1.70 \pm 0.3) \times 10^{-3}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[22]
L483	$(2.20 \pm 0.4) \times 10^{-3}$	HDO/H <sub>2</sub> O (H <sub>2</sub> <sup>18</sup> O)	[22]

Note: not all measurements use the same method, but when the method is not HDO/H<sub>2</sub>O, their values are translated into the equivalent HDO/H<sub>2</sub>O by multiplying by a factor of 2 because HDO/H<sub>2</sub>O=2×D/H. See refs. <sup>21,22,24,26,60-73</sup>.