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Unexpected increase in water abundance and the deuterium-to-hydrogen ratio observed in Venus's mesosphere

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Until the ESA Venus Express mission, the Venus mesosphere was a poorly understood region of the Venus's atmosphere. This mission, which operated between 2006 and 2014, revealed the composition and thermal structure of the mesosphere and lower thermosphere (Titov et al., 2006, Vandaele et al., 2017, Limaye et al., 2018, Marcq et al., 2018) with the help of its suite of instruments: VIRTIS (Drossart et al., 2007), SPICAV-IR and SPICAV-UV (Bertaux et al., 2007), SOIR (Nevejans et al., 2006). The spacecraft counted a suite of eight instruments, amongst which the SOIR (Solar Occultation in the InfraRed) instrument, which was an echelle grating infrared spectrometer operating exclusively in Solar Occultation mode.

This study focuses on the H_2O, HDO, and temperature vertical profiles. The HDO/H_2O ratio in its bulk atmosphere is 120 times Earth's (Donahue et al., 1982, de Bergh et al., 1991, Gurwell et al., 2007, Krasnopolsky et al., 2013, Encrenaz et al., 2015, Tsang et al., 2017). We report a significant increase in the H_2O and HDO volume mixing ratios with altitude, with the D/H ratio rising significantly from 0.025 at ~70 km to 0.24 at ~108 km. This indicates an increase from 162 to 1519 the Earth's ratio within 40 km.

Our work explores two hypotheses to explain these observations: isotopic fractionation from photolysis of H_2O over HDO (Liang et al., 2009) or from phase change processes. We show that the first one cannot explain the observations. The latter, involving condensation and evaporation of sulfuric acid aerosols, as suggested by previous authors (Zhang et al., 2010, Karyu et al., 2024), aligns more closely with the rapid changes observed. Vertical transport computations for H_2O, HDO, and aerosols show water vapor downwelling and aerosols upwelling.

We propose a mechanism where aerosols form in the lower mesosphere due to temperatures below the water condensation threshold, leading to deuterium-enriched aerosols. These aerosols ascend, evaporate at higher temperatures, and release more HDO than H_2O, which are then transported downwards. Moreover, this cycle would imply an SO_2 increase in the upper mesosphere, previously observed above 80 km by several authors (Belyaev et al., 2012, Mahieux et al., 2015).

The study highlights two crucial implications. First, altitude variation is critical to determining the

Venus deuterium and hydrogen reservoirs. Second, the altitude-dependent increase of the D/H ratio affects H and D escape rates. The photolysis of H_2O and HDO at higher altitudes releases more D, influencing long-term D/H evolution.

These findings suggest that evolutionary models should incorporate altitude-dependent processes for accurate D/H fractionation predictions.

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