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THE ORIGIN OF EXTERNAL OXYGEN IN JUPITER AND SATURN'S ENVIRONMENTS

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Abstract. This paper reviews the recent findings of the Herschel Solar System Observations Key Program (Hartogh et al. 2009b), as well as ground-based supporting observations, regarding the origin of external oxygen in the environments of Jupiter and Saturn. Herschel-HIFI and PACS observations have been used to shown that the Shoemaker-Levy 9 comet is the source of Jupiter's stratospheric water, and that Enceladus (and its geysers) are most probably the source of water for Saturn and Titan.

Keywords: Jupiter, Saturn, Titan – Atmospheres – Herschel

1 Introduction

The detection of H_2O and CO_2 in the stratospheres of the Giant Planets and Titan with the Infrared Space Observatory in the late 1990s (Feuchtgruber et al. 1997; Coustenis et al. 1998) raised the question of the origin of oxygen compounds in their upper atmospheres. Oxygen-rich deep interiors of the Giant Planets cannot explain this discovery because these species are trapped by condensation below their tropopauses (except CO_2 in Jupiter and Saturn). So, these species must come from external sources, which can be: (i) a permanent flux from interplanetary dust particles (IDP) produced from asteroid collisions and comet activity (Prather et al. 1978), (ii) local sources from planetary environments (icy rings and satellites) (Strobel & Yung 1979; Connerney 1986; Prangé et al. 2006), and/or (iii) cometary Shoemaker-Levy 9 type impacts (Lellouch et al. 1995). Disentangling the various sources at Jupiter and Saturn was a key objective of the Herschel key program HssO (Herschel Solar System Observations) (Hartogh et al. 2009b). In this paper, we will review the recent results obtained with Herschel-HIFI and -PACS (Pilbratt et al. 2010; de Graauw et al. 2010; Poglitsch et al. 2010) on the origin of external oxygen in Jupiter and Saturn's environments. These results are presented in more details in Cavalié et al. (2013), Hartogh et al. (2011), and Moreno et al. (2012).

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2 Jupiter

Observations carried out in the late 1990s have shown that CO* and CO_2 have been delivered by the Shoemaker-Levy 9 (SL9) comet impacts in Jupiter's southern hemisphere in July 1994 (Bézard et al. 2002; Lellouch et al. 2002). Despite a number of converging indications that H_2O in Jupiter also originates from the SL9 event, the direct proof, i.e., the evidence for spatial variations of H_2O in Jupiter, was missing prior to Herschel (Bjoraker et al. 1996; Bergin et al. 2000; Lellouch et al. 2002; Cavalié et al. 2008, 2012).

Water has been mapped in Jupiter with the Wide Band Spectrometer (WBS) of HIFI on July 7, 2010, at 1669.9 GHz (179.5 μm).In addition, a water map at 66.44 μm (= 4512 GHz) has been obtained with the 5×5 receiver array of PACS on December 15, 2010. A full description of the HIFI and PACS data reduction is given in Cavalié et al. (2013). The observed lines depend on both the stratospheric temperature and H_2O abundance. This is why temperature was monitored with the NASA Infrared Telescope Facility (IRTF) in parallel.

The HIFI and PACS observations show consistently that the emission was stronger in the southern hemisphere of the planet. All lines have been modeled with a 1D radiative transfer code detailed in Cavalié et al. (2008, 2014). Both temperature and abundance variability has been investigated. Stratospheric temperature maps have been compared to the IRTF observations and they are in disagreement. Therefore, temperature is not the cause of the hemispherical asymmetry seen in the water emission. It is then due to an asymmetry in the water latitudinal distribution. The HIFI and PACS maps show consistently that there is 2-3 times more water in Jupiter's southern hemisphere than in its northern hemisphere (see Fig. 1). This is thus interpreted as a an aftermath of the SL9 impacts of 1994 that occurred at 44°S. An IDP source should have produced a more uniform distribution. Moreover, the spectrally resolved HIFI lines enable to constrain the vertical distribution of the bulk of stratospheric water. It is found that water resided at pressures p <2 mbar, also in agreement with expectations from a comet impact in 1994 (Moreno et al. 2003) and in disagreement with an IDP source (Cavalié et al. 2012).

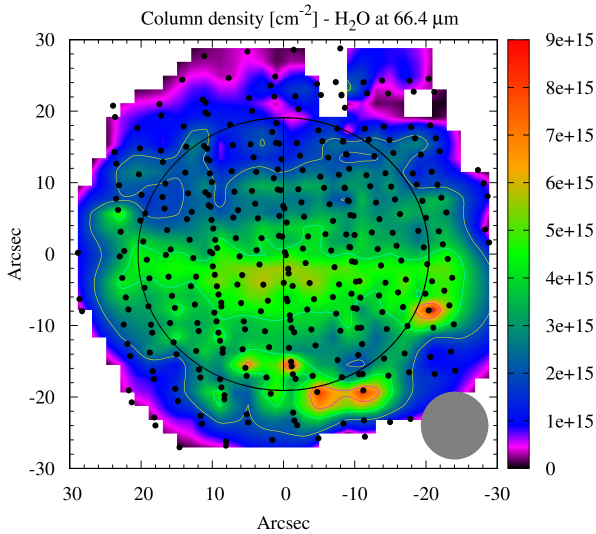

Fig. 1. Column density of water (in cm^{-2}) in Jupiter's stratosphere derived from the PACS map at 66.4 μm. Black ellipse: Jupiter; black vertical line: Jupiter's rotation axis; gray filled circle: PACS beam; black dots: observation pointings. *(Fig. 15 from Cavalié et al. 2013)*

3 Saturn

A decade after the ISO detection of external water in the giant planet stratospheres, the Cassini probe discovered geysers at the south pole of Saturn's moon Enceladus (Hansen et al. 2006; Porco et al. 2006). These geysers

*Bézard et al. (2002) additionally found that the jovian CO also originated from ancient SL9-type impacts and from an internal source.

are mainly composed of water (Waite et al. 2006). In 2009-2010, Herschel-HIFI observed Saturn to determine the vertical profile of water and hence its origin. However, the observations at 557 GHz did not lead to the expected emission line previously observed by Bergin et al. (2000), but to an intriguing spectral feature with wings in emission and a strong absorption at the core. Hartogh et al. (2011) have demonstrated by developing appropriate excitation and torus models that the absorption is due to a cold torus of gaseous water located at the orbital distance of Enceladus, which was shadowing Saturn from Herschel (see Fig. 2 left). In 2009, the ring plane was indeed crossing the observer plane.

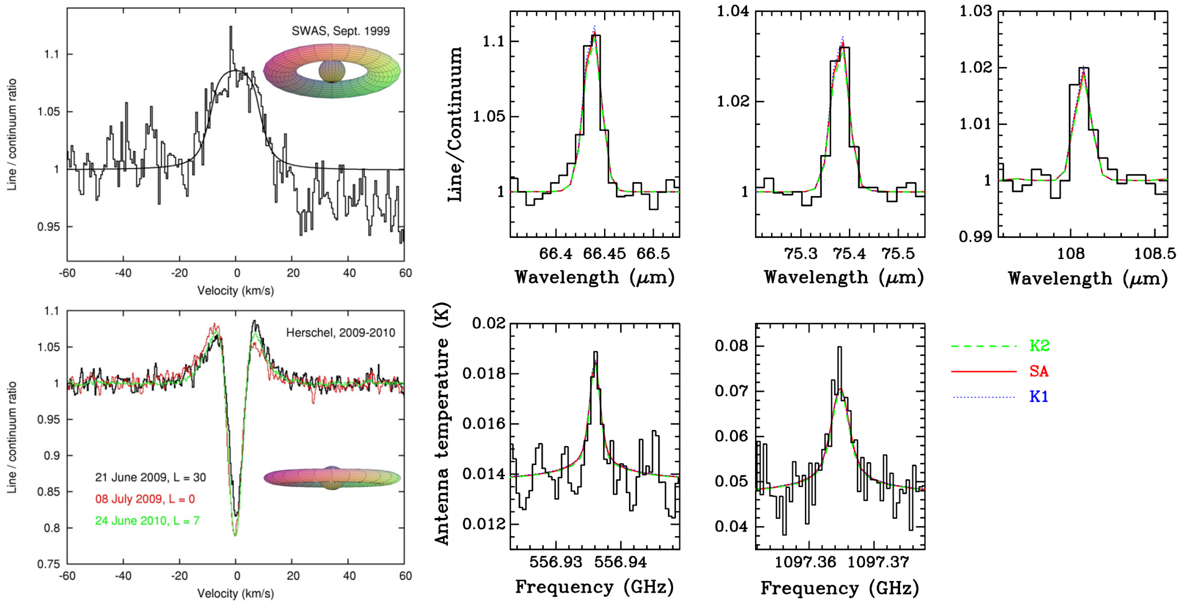

Fig. 2. *Left:* H_2O line at 557 GHz, as observed by SWAS in 1999 (Bergin et al. 2000) and by Herschel in 2009-2010 (Hartogh et al. 2011) with sub-observer latitudes of $-21°$ and $\sim 0°$, respectively. The absorption core seen in 2009-2010 is caused by a torus of gaseous water located at the orbital distance of Enceladus. *Right:* Observations of water in Titan with HIFI and PACS in 2010-2011. *(Figs. 1 and 3 from Hartogh et al. (2011) and Moreno et al. (2012), respectively)*

The temporal evolution of the Enceladus torus, whose source is undoubtedly the Enceladus geysers, has been predicted by Cassidy & Johnson (2010) with a diffusion model in which water molecules scatter around the equatorial plane of Saturn due to molecular collisions. This model predicts a small fraction of the torus water eventually rains onto Saturn's stratosphere. The next step of this work is to take the water influx predictions of Cassidy & Johnson (2010) into account in a latitude-altitude photochemical model to derive the spatial distribution of water in Saturn's stratosphere and to compare it to PACS disk-resolved observations of water (Cavalié et al., in prep.). Interestingly, ground-based observations have shown that CO in Saturn's stratosphere probably originates from a large comet impact, rather than from another source (e.g. Enceladus).

4 Titan

Moreno et al. (2012) have observed water lines in Titan's atmosphere with Herschel-HIFI† and -PACS in 2010-2011. The analysis of the lines (see Fig. 2 right), combined with the development of a new photochemical model, led to new constraints on the water vertical profile. The water influx is 10 times less than required to match the observed CO_2 mole fraction. However, water has a shorter atmospheric lifetime than CO_2 (9 years vs 450 years) so that the oxygen influx into Titan could be much smaller currently than its average value over the past centuries.

Moreno et al. (2012) have shown that both an interplanetary particle source or Enceladus can provide enough water to Titan, but Enceladus was tentatively favored as this source is more prone to temporal variability. A

†Interestingly, the HIFI observations led to the fortuitous detection of HNC (Moreno et al. 2011).

recent paper by Lara et al. (2014) has shown with photochemical computations that Enceladus is indeed a more favorable source than any other. A decrease of the Enceladus source by a factor of 5 to 20 is required over the last few centuries to reconcile the water and CO_2 observations.

5 Conclusions

Jupiter The SL9 source is now confirmed for Jupiter's stratospheric water (Cavalié et al. 2013). The monitoring of SL9-derived species will continue in the next years to constrain Jupiter's dynamics and to prepare for future JUICE/SWI observations (Hartogh et al. 2009a).

Saturn and Titan There are strong and consistent indications that Enceladus is the ultimate source of water in Saturn's environment (Hartogh et al. 2011; Moreno et al. 2012; Lara et al. 2014). The PACS observations of Saturn (Cavalié et al., in prep.) may provide additional proof by validating the model of Cassidy & Johnson (2010). Regarding Titan, complementary clues are needed to firmly validate the Enceladus source, like the detection of other molecules from coming from this moon in Titan's atmosphere (Dobrijevic et al. 2014; Hickson et al. 2014).

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