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MAPPING CO IN SATURN'S STRATOSPHERE BEFORE AND DURING THE LAST GREAT STORM

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Abstract. In December 2010, a major seasonal storm appeared in Saturn's troposphere at approximately 40° north latitude and caused a great white spot. This type of phenomenon occurs every 30 years, which corresponds approximately to the orbital period of the planet. This storm produced a hot vortex in Saturn's stratosphere that persisted for about 3 years. Our goal is to check whether material from Saturn's troposphere could have been transported into this vortex by the storm. This would then represent a unique opportunity to probe the internal composition of Saturn, and to possibly be able to bring new constraints on its formation. In March 2010, a few months before the storm, we mapped the spatial distribution of CO, a trace species in Saturn's stratosphere, with the Submillimeter Array (SMA), allowing us to have a reference value of the CO abundance. Then in January 2012, while the stratospheric vortex of the storm was still active, we made new observations of CO with the ALMA interferometer. These two observation windows allow us to compare the CO abundance before and during the storm and to determine its temporal evolution thanks to radiative transfer modelling.

We obtain that the storm had no significant effect on the latitudinal distribution of CO and that there was no CO transported from the troposphere to the stratosphere. The latitudinal distribution of CO we derive is relatively unifrom over the entire planet.

Keywords: Saturn, Atmosphere, CO, ALMA, Great Storm

1 Introduction

In December 2010, a spectacular event occurred on Saturn: the onset of a gigantic storm in the form of a large white spot, of a size equivalent to that of the Earth, at approximately 40°N. During 2011, the cloudy storm spread in the troposphere eventually encircling the planet in May 2011. This atmospheric disturbance also had a stratospheric counterpart, in the form of a hot vortex (Fletcher et al. 2011), observable in infrared for about 3 years. The latter was particularly exceptional, due to its duration, its extent in latitude and longitude and the extreme warming in the middle stratosphere (Fletcher et al. 2012). The event was monitored by Cassini (1997-2017), the Hubble Space Telescope (HST), many ground observatories and amateur astronomers (e.g. Sánchez-Lavega et al. 2012, Hesman et al. 2012, Baines et al. 2018). This made it possible to collect a large amount of data and to achieve a detailed study of the phenomenon. Our goal is to investigate whether chemistry of oxygen species was disrupted by the hot stratospheric vortex by transporting CO from the troposphere (Fouchet et al. 2017) to the stratosphere at this location.

To do so, we compared the spatial distribution of CO before and during the existence of this hot stratospheric vortex. The first observation was initially performed with the aim to constrain the origin of external CO in Saturn's stratosphere. The question was, in fact, whether the CO observed in the stratosphere of the planet came from a comet impact (Cavalié et al. 2010), from icy rings and/or satellites as for H_2O (Cavalié et al. 2019), or from interplanetary dust particles (Moses & Poppe 2017).

In this paper, we present CO line observations performed with the Submillimeter Array (SMA) and Atacama Large Millimeter/submillimeter Array (ALMA) interferometers before and during the existence of the

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hot stratospheric vortex. In Sect. 2, we describe the observations and the data reduction. We then describe the radiative transfer model that we used in Sect. 3 and discuss the results obtained from our modelling in Sect. 4. We finally present our conclusions and perspectives in Sect. 5.

2 Observations

We observed the CO(3-2) line emission around 345 GHz with the SMA on March 13th, 2010, in Saturn's atmosphere. These data have been bandpass, flux and phase calibrated. Despite the very good weather conditions during these observations (pwv ∼0.5mm), the data suffer from strong bandpass ripples that vary with time and that are stronger than the line emission. Their removal proved to be difficult and unperfect. The SMA also only had six of eight antennas working on the night of observations, limiting our ability to image such a complex and large source. However, we managed to image the planet and produce a spectral image of the CO(3-2) emission. The size of the synthetic beam was 5.0"x4.7" and the spectral resolution was 812.5 kHz. We finally extracted the lines from the spectral cubes at the position of the planet limb (i.e. where they are the strongest to maximize signal-to-noise ratio) for analysis. The lines are spectrally shifted by the rapid planet rotation (9.9 km/s at the equator). This map is meant as a pre-strom reference regarding the CO spatial distribution.

We also observed the CO(2-1) line at 230 GHz in Saturn's stratosphere with ALMA on January 9th, 14th and 22th, 2012. The synthetic beam size during observations was 2.04"x1.34" and the spectral resolution was 244.1 kHz. These data have been calibrated and concatenated before producing the spectral image. They allow us to get the spatial distribution of CO, while the storm's stratospheric counterpart was located on the planetary eastern limb during the observations. We can then evaluate whether the storm induced any change in the spatial distribution of CO within the vortex.

3 Model

We used a radiative transfer model to fit the data and constrain the spatial distribution of CO in Saturn's stratosphere during the two observed epochs. The model initially developed in 1D by Cavalié et al. (2008) was upgraded to fully account for the 3D ellipsoidal geometry of the planet and its ring system by Cavalié et al. (2019). We used temperature profiles measured by Fletcher et al. (2012) for the vortex and by Fletcher et al. (2016) for other latitudes and the disk-averaged CO vertical profile determined by Cavalié et al. (2010). We then simply applied scaling factors to the CO profile to fit the lines at the various pointings on Saturn limb as in the example shown in Fig. 1.

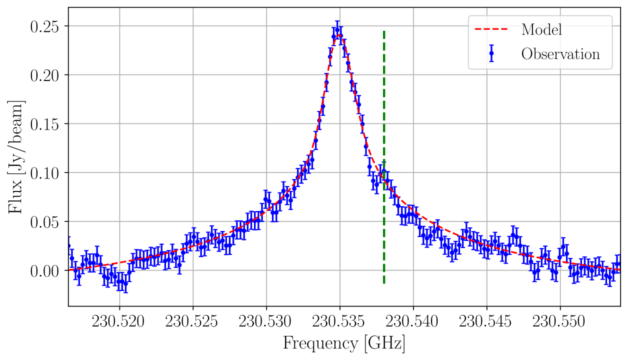

Fig. 1: Example of fit of a CO spectral line on the Saturn eastern limb at 230 GHz observed with ALMA and obtained with our radiative transfer model. The green vertical bar indicates the line rest frequency, showing that the line is Doppler-shifted by the planet rapid rotation.

4 Results and discussion

Fig. 2 presents the meridional distribution of the CO column density in Saturn's stratosphere, as derived from the two observations. The SMA data seem to indicate that there is significant longitudinal variability between the eastern and western limbs. On the eastern limb, we find a slight increase of the column density from the south to the north of a factor of 1.4±0.8. On the other hand, on the western limb, there is much more variability as a function of latitude and with respect to the other limb, including a broad peak centered around 20°N in which the CO column is up to 4 times larger than at other latitudes. This western column density profile looks questionable for two reasons: (i) such longitudinal variability is not expected in an atmosphere where the temperature is almost zonally uniform (Fletcher et al. 2016), and (ii) zonal transport timescales are much shorter than timescales involved in any of the potential CO external sources making such peak unlikely unless there was a very recent and big comet impact at this latitude and longitude like the Shoemaker-Levy 9 impacts in Jupiter (Lellouch et al. 1995). Such impact has not been observed despite the presence of the Cassini spacecraft in the Saturn system since 2004. The questionable variability of the column density profile derived at the western limb in the SMA data is probably results from the limitations of the bandpass ripple removal. One further idea to bolster that the E-W variation is probably not real is that the SMA observations occurred over several hours, and thus anything located around a particular longitude would be smeared substantially by nearly half of a Saturn rotation. It is still possible that something isolated in local time (that is if there was some chemistry driving a big increase in CO near one terminator vs the other) that could explain a difference. The problem is that the CO chemistry is likely much slower than that. It seems that nothing could create a difference in abundance of the magnitude that the SMA supposedly shows and that would be fixed in local time while the planet rotates very fast on itself.

The eastern limb column density profile derived from the ALMA data shows a dramatic increase around 20°S. The increase is not as significant on the western limb. This is most likely caused by the effect of the rings at these latitudes. Indeed, the sub-observer latitude was 18.2°, in January 2012. It was only 4.2°, in March 2010, leaving the spectra unhampered by the rings in the SMA data. First, the spectral image shows large variability in the continuum between the two limbs at the location obscured by the rings. Second, the model also fails at reproducing the ALMA spectra in the region obscured by the rings. This can be explained by the fact that we must interpolate centimeter and infrared data regarding ring brightness temperatures and opacities in the millimeter range, because of the lack of data. We therefore simply ignore the data in this latitude range on both limbs, as indicated by the gray rectangle in Fig. 2. On the western limb, the CO meridional distribution seems to be uniform within error bars with latitude.

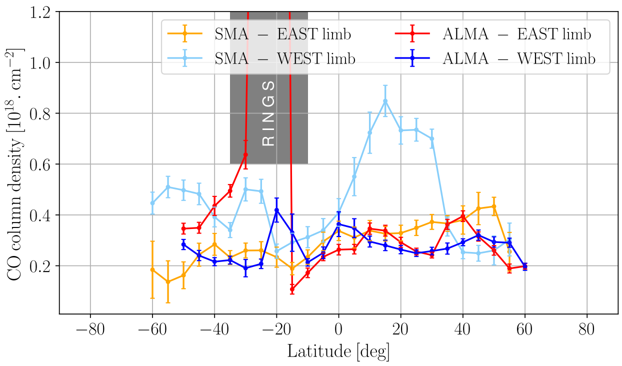

Fig. 2: CO column density as a function of latitude on the eastern and western limbs as derived from SMA and ALMA observations (taken at 345 GHz and 230 GHz, respectively). 1-σ uncertainties resulting from the fitting are displayed.

When comparing the column density meridional profiles derived from the two observations and ignoring the latitude interval perturbed by the shadow of the rings in the ALMA data (15°S-30°S), we find that the ALMA observations reproduce, within uncertainties, the eastern limb data of the SMA. The CO column density remains meridionally uniform with a value of $(3\pm1)\times10^{17}$ cm^{-2}. This result tends to confirm that we should not believe the western limb column density profile derived from the SMA data.

The hot vortex produced by the great storm was located at 40° N and spread over more or less 10° of latitude either side. The vortex was located at the planet eastern limb during the ALMA observation. At this position, there is no significant increase in the ALMA data. This result seems to indicate that the storm, despite its intensity, did not disrupt the latitudinal CO distribution in Saturn's atmosphere by transporting tropospheric CO to the stratosphere.

This result is in agreement with the study by Greathouse et al. (2011) on the distribution of NH_3 and PH_3 in Saturn's stratosphere. While these species are found in Saturn's troposphere (e.g. Fletcher et al. 2012), Greathouse et al. (2011) did not find them in the hot stratospheric vortex.

We can underline the fact that the disk-averaged profile derived by Cavalié et al. (2010) by assuming a comet source for CO successfully reproduces the observed lineshapes after applying a global scaling factor of 3.6±0.4. This seems to reinforce the comet impact hypothesis to explain externally sourced CO in Saturn's stratosphere. The fact that the CO column density was meridionally uniform as of 2010-2012 implies that the putative comet impact occurred several decades ago, as proposed by Cavalié et al. (2010).

5 Conclusions

In this paper, we have compared CO mapping observations obtained with the SMA in March 2010, i.e. before the onset of Saturn's most recent great storm, and with ALMA in January 2012, i.e. when the hot stratospheric vortex resulting from the storm was still active. This has allowed us to obtain the column density of CO as a function of latitude before and during the great storm. It appears that the storm was not intense enough to transport CO from the troposphere to the stratosphere at the location of the vortex. The CO distribution seems in fact rather homogeneous over the whole planet, with a column density of $(3\pm1)\times10^{17}$ cm^{-2}.

Finally, we have seen that the cometary-sourced CO vertical profile from Cavalié et al. (2010) reproduce the observed lineshapes, which seems to be additional evidence that a comet impact would be the source of Saturn's stratospheric CO. We should now investigate whether there is a vertical profile that allows us to reconcile the SMA and ALMA observations with the JCMT (James Clerk Maxwell Telescope) disk-averaged observations (Cavalié et al. 2010). The various data could probe slightly different altitudes and enable us to constrain a unique CO vertical profile to fit them all.

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References

Baines, K. H., Flasar, F. M., Krupp, N., & Stallard, T., eds. 2018, Saturn in the 21st Century, Cambridge Planetary Science (Cambridge: Cambridge University Press)

Cavalié, T., Billebaud, F., Biver, N., et al. 2008, Planetary and Space Science, 56, 1573

Cavalié, T., Hartogh, P., Billebaud, F., et al. 2010, Astronomy and Astrophysics, 510, A88

Cavalié, T., Hue, V., Hartogh, P., et al. 2019, Astronomy and Astrophysics, 630, A87

Fletcher, L. N., Hesman, B. E., Achterberg, R. K., et al. 2012, Icarus, 221, 560

Fletcher, L. N., Hesman, B. E., Irwin, P. G. J., et al. 2011, Science, 332, 1413

Fletcher, L. N., Irwin, P. G. J., Achterberg, R. K., Orton, G. S., & Flasar, F. M. 2016, Icarus, 264, 137

Fouchet, T., Lellouch, E., Cavalié, T., & Bézard, B. 2017, in American Astronomical Society/Division for Planetary Sciences Meeting Abstracts #49, 209.05

Greathouse, T. K., Irons, W., Fouchet, T., et al. 2011, in American Geophysical Union, Fall Meeting Abstracts, Vol. 2011, P13C–1682

Hesman, B. E., Bjoraker, G. L., Sada, P. V., et al. 2012, The Astrophysical Journal, 760, 24

Lellouch, E., Paubert, G., Moreno, R., et al. 1995, Nature, 373, 592

Moses, J. I. & Poppe, A. R. 2017, Icarus, 297, 33

Sánchez-Lavega, A., del Río-Gaztelurrutia, T., Delcroix, M., et al. 2012, Icarus, 220, 561