



HCl variability in the Martian atmosphere observed with ExoMars - TGO / NOMAD during 6 years of solar occultations

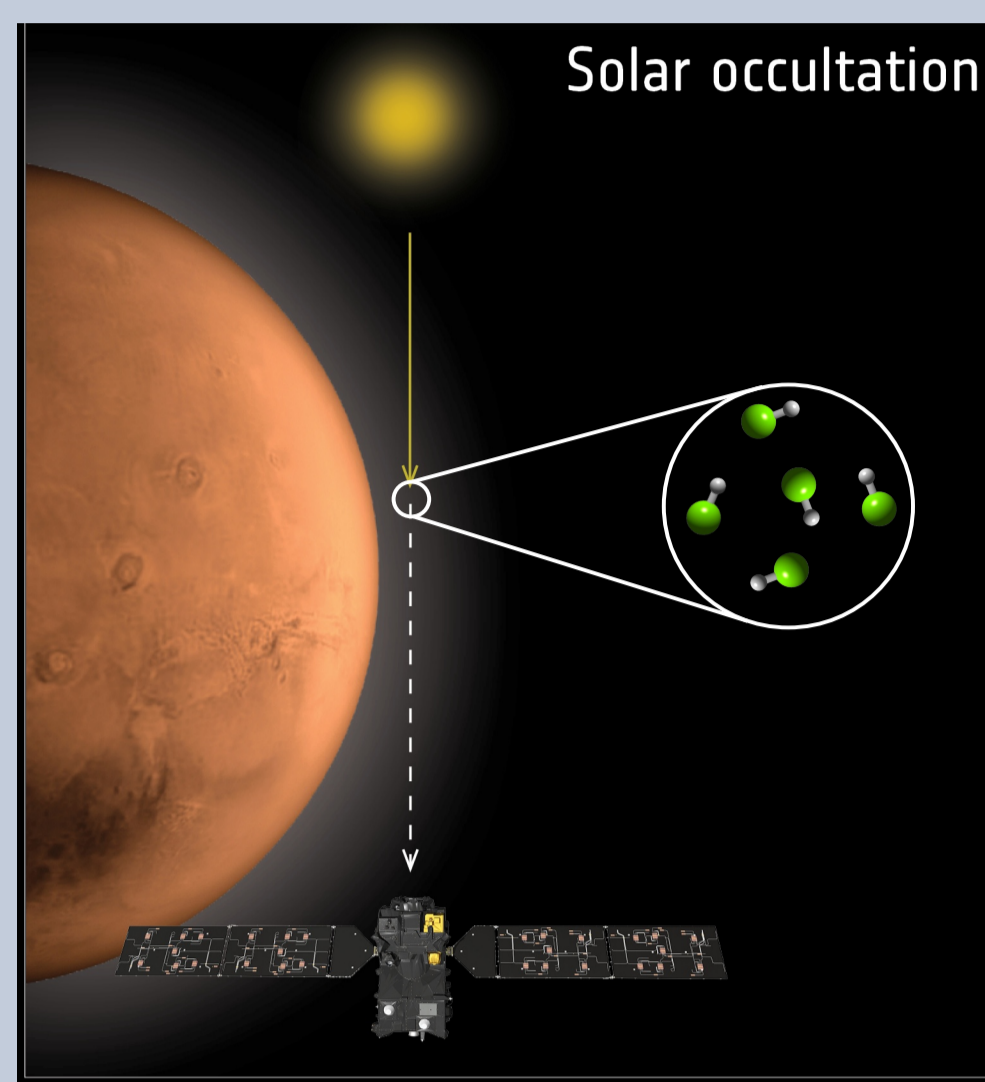
A. Brines¹, A. Belmonte¹, M. A. López-Valverde¹, B. Funke¹, A. Stolzenbach¹, A. Modak^{1,10}, F. G. Galindo¹, S. Aoki^{2,3}, G. L. Villanueva⁴, G. Liuzzi⁵, I. R. Thomas², J. T. Erwin², U. Grabowski⁶, F. Forget⁷, J.J. Lopez-Moreno¹, J. Rodriguez-Gomez¹, R. M. Sanz-Mesa¹, F. Daerden², L. Trompet², B. Ristic², M. R. Patel⁸, G. Bellucci⁹ and A. C. Vandaele²

¹Instituto de Astrofísica de Andalucía (IAA/CSIC), Spain; ²Royal Belgian Institute for Space Aeronomy, Belgium; ³NASA GSFC, USA; ⁴University of Basilicata, Italy; ⁵Karlsruhe Institute of Technology, Germany; ⁶Météorologie Dynamique, IPSLnc; ⁷Open University, UK; ⁸INAF-IAPS, Italy; ⁹Instituto de Astrofísica e Planetologia, Italy; ¹⁰Institute for Basic Science, South Korea



1. Motivation

HCl, although until now considered to be a negligible species in the Martian atmosphere [1, 2], it has been recently **detected** systematically by two instruments onboard Trace Gas Orbiter (TGO): the Atmospheric Chemistry Suite (ACS) [3] and NOMAD [4]. Several works suggest the surface of Mars to be a source of chloride minerals and perchlorate salts [5], which along with interactions surface-atmosphere could allow for chlorine photochemistry happening on the martian atmosphere. On Earth, one of the main sources of HCl is the volcanic activity [6], so the detection of this species on Mars may be an indicator of active **geological processes**. Multiple ongoing studies are trying to characterize the climatology of HCl on Mars, currently **not completely understood**, looking for possible relationships between temperature and other atmospheric species such as **dust** or **water vapor**.



We present here recent results devoted to characterize the HCl in the Martian atmosphere, extending its study to three Martian Years (MY). **Two independent studies** have been performed at the IAA-CSIC in order to identify **HCl detections** [7] and to obtain **vertical profiles** up to 60 km altitude.

In **Section 2** we present the **NOMAD instrument** and the data analysis **methodology** of both independent studies. In **Sections 3** and **4** we show the main **results** of each methodology. Finally, **Section 5** summarizes the main **conclusions** of this work.

Fig. 1: Schematic of Solar Occultation geometry

2. NOMAD Data Analysis at IAA-CSIC

NOMAD is an infrared spectrometer covering the spectral range between 0.2 to 4.3 μm . Its SO channel uses an Echelle grating with an Acousto-Optical Tunable Filter (AOTF) to select different diffraction orders to be used during the observations. The spectral resolution of the SO channel is $\lambda/\Delta\lambda = 17,000$. The sampling allows a **vertical resolution of about 1 km**. Also, the AOTF permits probing the atmosphere at a given altitude through 6 different diffraction orders [8].

In addition to the **HCl**, our processing pipeline has been optimized to retrieve **vertical profiles of temperature** [9], **water vapor** [10], [11], [12], **carbon monoxide** [13] and **aerosol** [14], providing a wide overview of the Martian atmosphere.

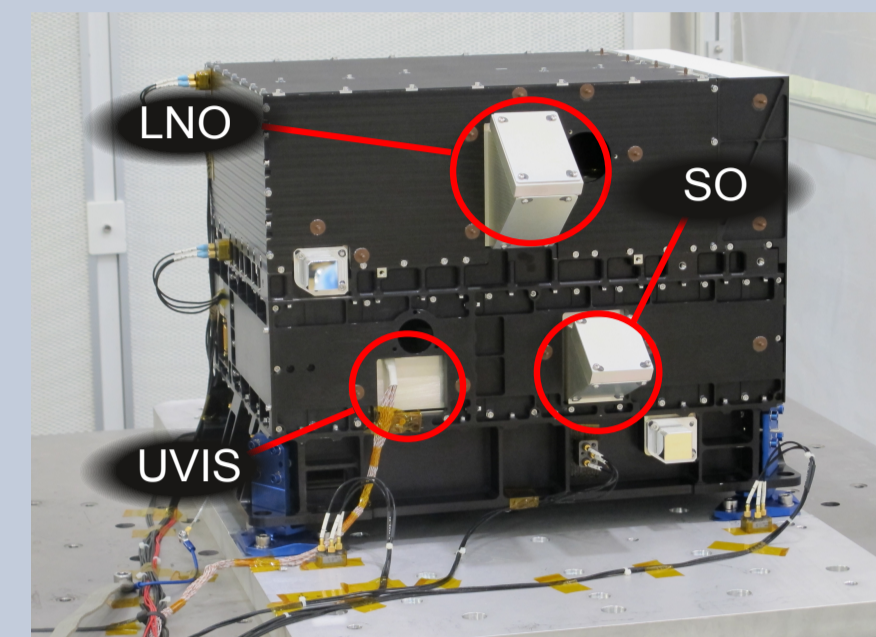


Fig. 2: The NOMAD instrument with its Solar Occultation (SO), Limb/Nadir Observation (LNO) and UV-visible (UVIS) channels.

For this study, we used Level 1 SO calibrated **transmittances** [15], [16] of diffraction orders **129** (2899 - 2922 cm^{-1}) and **130** (2921 - 2945 cm^{-1}). Our **pre-processing pipeline** identifies and corrects for residual artifacts in the spectra (bending, spectral shift) using the **line-by-line radiative transfer algorithm KOPRA** [17]. Two independent methods have been developed at the IAA-CSIC to obtain HCl abundance:

Method A: A pre-calculated data set of **KOPRA** simulated spectra is used to fit the NOMAD data, allowing for an estimation of the **HCl abundance** when the absorption of the expected HCl line is larger than **3 σ** over the spectral continuum [7].

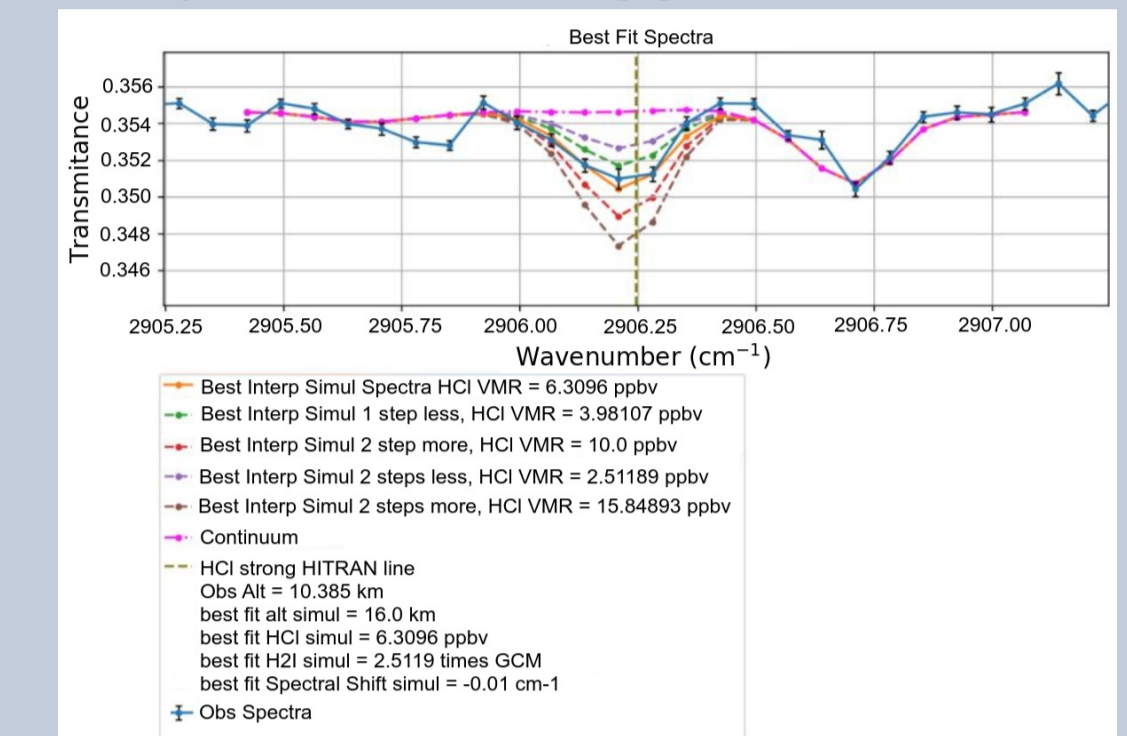


Fig. 3: NOMAD SO spectra (blue) from diffraction order 129 and KOPRA simulations for different HCl abundances. Vertical dashed line indicates the location of the HCl absorption line.

Method B: We have applied an extension of our previous water vapor **retrieval setup** [12], improving the continuum characterization and performing three independent inversions (**state-of-the-art global fit**) of the data from **three detectors bins** in the NOMAD SO channel. The three retrieved vertical profiles are then **averaged** at those altitudes where all of them show abundances above our detection limits. During the inversions, we implemented into our Forward Model KOPRA the latest calibration of the NOMAD AOTF and its instrumental line-shape (ILS) [18].

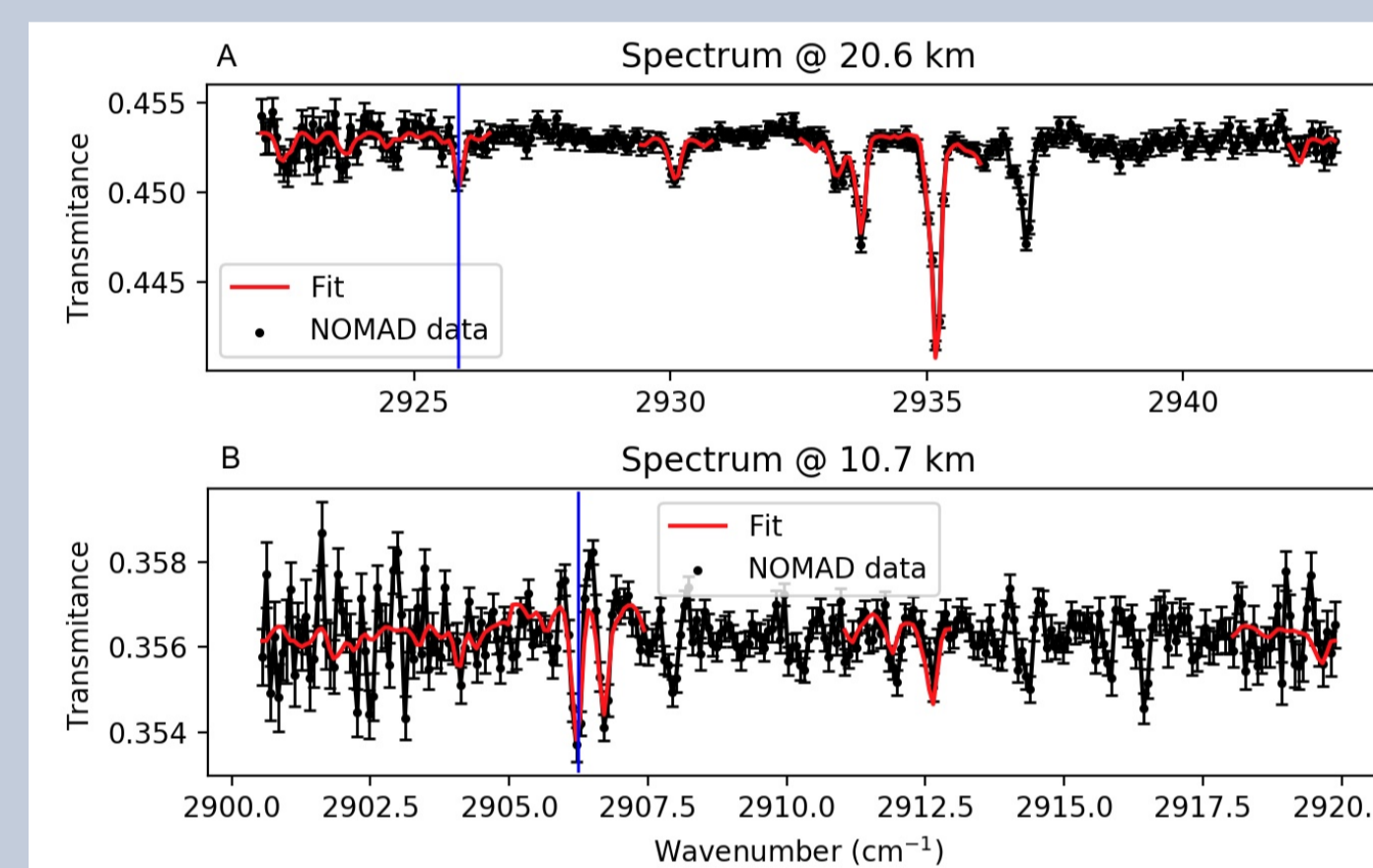


Fig. 4: NOMAD SO spectra (black) from diffraction orders 130 at 20 km altitude (panel A) and 169 at 10 km altitude (panel B). Red line shows the best fit of the forward model at the HCl and water vapor absorption lines obtained during the retrieval. Blue vertical line indicates the HCl line.

The best fit obtained during the inversion is good. This is illustrated in Fig. 3 with two examples of typical NOMAD spectra (black) after its bending and spectral shift corrections for diffraction orders 130 (panel A) and 129 (panel B) at 30 and 10 km respectively. We also show the fitting after the retrieval (red). For optimization purposes, we only fit the data at certain spectral windows where the strongest HCl and H_2O absorption lines are located.

3. Results: Method A

We applied this method to all spectra from **orders 129 and 130** available in the NOMAD data base for **Martian Years 34 and 35**. Here we present the **geographical and temporal distribution** of HCl in the Martian atmosphere.

We observe most of the **detections at $240^\circ < L_s < 320^\circ$** (perihelion season) at $\pm 45^\circ$ latitude and between **15-25 km altitude**. We do not observe a preferent geographical longitude for the HCl detections. Our analysis suggests larger HCl abundances in the **southern hemisphere**, possibly linked to the larger water vapor abundances at this hemisphere during this season.

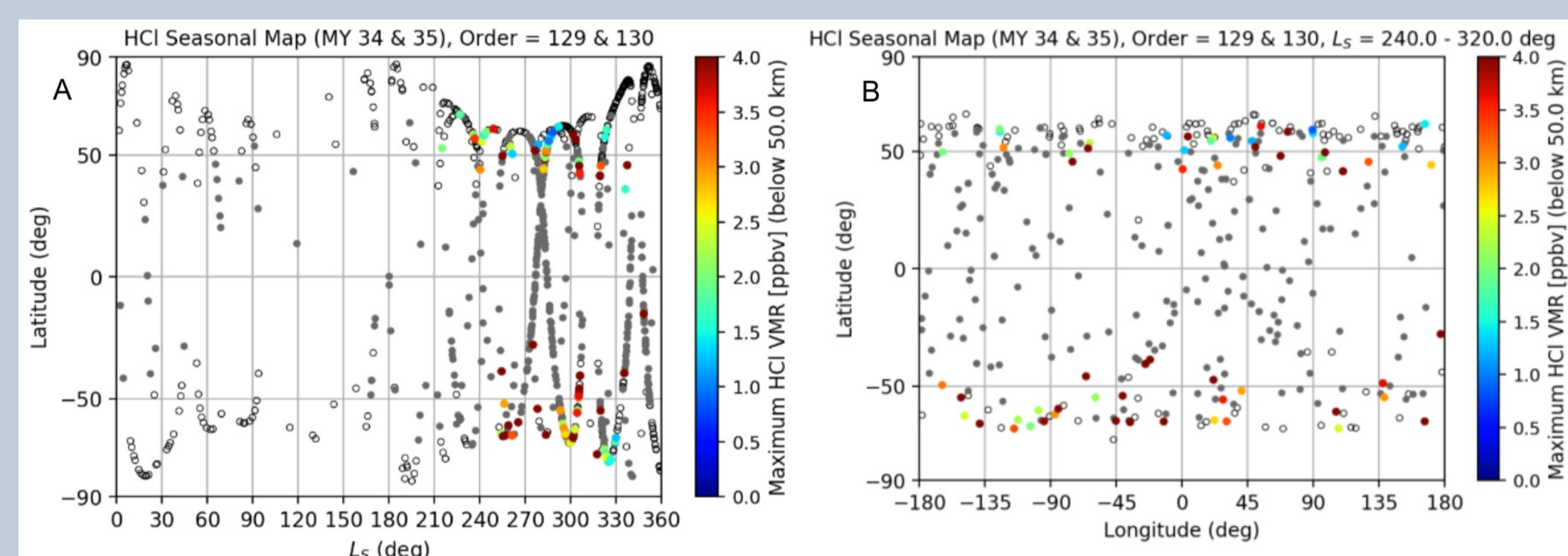


Fig. 5: Temporal (panel A) and geographical (panel B) distribution of HCl below 50 km altitude for MYs 34 and 35. Observations in panel B range from $L_s = 240^\circ - 320^\circ$. Empty and gray circles indicate non detections and high dust opacity respectively. Colors indicate HCl upper limit.

4. Results: Method B

We applied this method to all spectra from **orders 129 and 130** available in the NOMAD data base for the perihelion season of **Martian Years 34, 35 and 36**. Here we present preliminary results on the seasonal variability of the **HCl vertical distribution** between 0 - 60 km altitude. For the three MYs we observe the largest HCl abundances (~ 3 ppbv) confined between 10-30 km in the **southern hemisphere**, reaching 30 km altitude at $L_s = 270^\circ$ and decreasing in altitude toward $L_s = 300^\circ$. This period corresponds with the annual maximum in the southern hemisphere's **water vapor abundance** [11, 12]. In the northern hemisphere we observed scattered detections throughout the season. Method B improves upon Method A in that it performs a global-fit, instead of analyzing isolated altitudes, and that it computes the Averaging Kernel, which supplies the all-important Degrees-Of-Freedom (~ 7) and the actual vertical resolution (~ 5 -10 km).

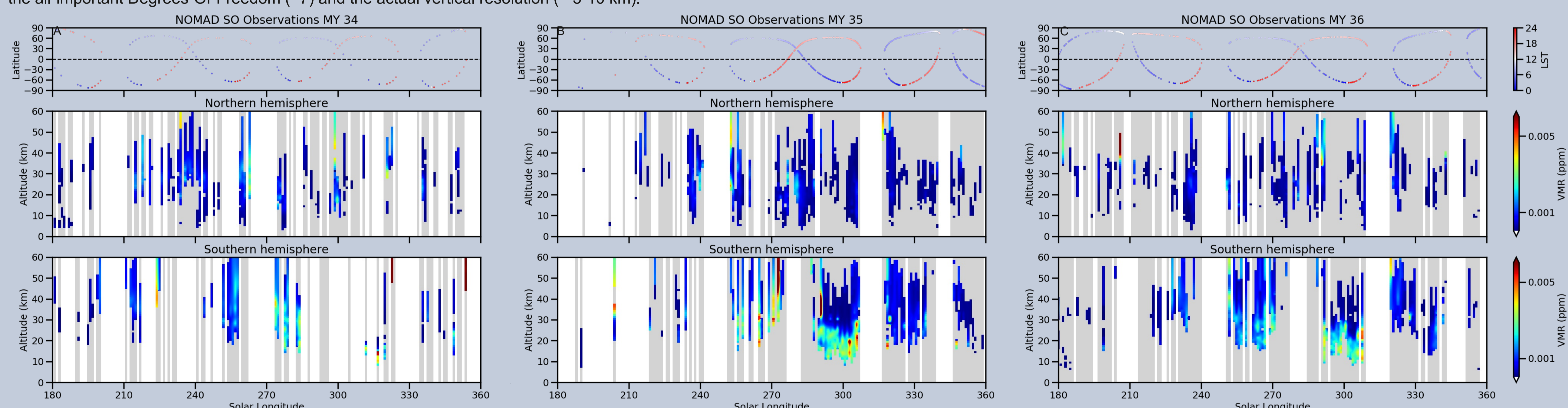


Fig. 6: Seasonal variability of the HCl vertical distribution for MYs 34 (A), 35 (B) and 36 (C). Top panels indicate the latitude and Local Solar Time of the NOMAD observations. Middle and bottom panels show the HCl abundance for the northern and southern hemispheres respectively.

5. Conclusions

We presented **two independent methods** devoted to the detection and characterization of the **HCl** in the Martian atmosphere using **NOMAD Solar Occultation** measurements. The main conclusions of this work are listed as follows:

- This is the **most extensive** and detailed analysis of HCl abundances with NOMAD SO to date, extending previous works by [4] to **3 MYs**, by performing **global-fitting** retrievals of vertical profiles including calculation of **DoF**, **vertical resolution** and a careful **error analysis**.
- Most of the **HCl detections** are observed during the second half of the Martian Year ($L_s = 180^\circ - 360^\circ$), specifically around the **perihelion** ($L_s \sim 250^\circ$).
- Both methods provide most of the detections between **10 - 40 km altitude**, whereas only method B is sensitive up to 60 km.
- The largest HCl abundance is observed in the **southern hemisphere**, although scattered detections are observed in the northern hemisphere.
- Our results are in line with those presented in previous HCl studies with NOMAD data [4].

References

[1] HARTOG, P. et al. 2010
 [2] VILLANUEVA, G. L. et al. 2013
 [3] KORABLEV, O. et al. 2021
 [4] AOKI, S. et al. 2021
 [5] GLAVIN, D. P. et al. 2013
 [6] GRAEDEL, T. et al. 1995
 [7] BELMONTE, A. Master Thesis. 2023
 [8] VANDAELE, A. C. et al. 2018
 [9] LÓPEZVALVERDE, M. A. et al. 2023
 [10] BRINES, A. et al. 2024a (accepted)
 [11] BRINES, A., PhD Thesis, 2024b
 [12] BRINES, A. et al. 2022
 [13] MODAK, A. et al. 2023
 [14] STOLZENBACH, A. et al. 2023
 [15] THOMAS, I. R. et al. 2022
 [16] TROMPET, L. et al. 2023
 [17] STILLER, G. P. et al. 2000
 [18] VILLANUEVA, G. L. et al., 2022

Acknowledgments

The IAA/CSIC team acknowledges financial support from the Severo Ochoa grant CEX2021-001131-S and by grants PID2022-137579NB-I00, RTI2018-100920-J-I00 and PID2022-141216NB-I00 all funded by MCIN/AEI/10.13039/501100011033. A. Brines acknowledges financial support from the grant PRE2019-088355 funded by MCIN/AEI/10.13039/501100011033 and by 'ESF Investing in your future'. ExoMars is a space mission of the European Space Agency (ESA) and Roscosmos. The NOMAD experiment is led by the Royal Belgian Institute for Space Aeronomy (IASB-BIRA), assisted by Co-PI teams from Spain (IAA- CSIC), Italy (INAF-IAPS), and the United Kingdom (Open University). AM was supported by the Institute for Basic Science (IBS-R035-C1).



8 - 13 September 2024
Berlin, Germany

