Recent observations of the Martian climate and trace gases with ExoMars Trace Gas Orbiter

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Introduction:

Accurate forecasting of the Martian past requires accurate climate data from the present. The ExoMars Trace Gas Orbiter (TGO) has been making observations of the Martian atmosphere with unprecedented sensitivity since 2018, following on from successful missions such as Mars Express and Mars Reconnaissance Orbiter (MRO). Recent work by the ExoMars TGO Science Working Team included detailed climatologies of the water vapour and temperature measurements made with ACS, and a comparison with the dust and water ice aerosols measurements made with the MRO Mars Climate Sounder (MCS). In this presentation, we will go over recent highlights from the ACS investigation, focusing on the seasonal climate variability of key atmospheric parameters. We will then focus in on target trace gases that could tell us about the history of the Martian climate: organic molecules (not seen), sulfur-bearing molecules (not seen), and chlorine-bearing molecules (hydrogen chloride, HCl, detected with ACS). These gases are informative of past volcanic states and the habitability of Mars, and their modern presence has implications that will be discussed.

ACS on ExoMars TGO:

ACS MIR is a cross-dispersion spectrometer on TGO that operates in solar-occultation mode. It consists of an optical telescope that makes direct observations of the sun, an echelle grating whose diffraction orders are in the infrared, and a secondary, steerable grating that separates overlapping diffraction orders. The secondary grating is steerable, and its position determines the instantaneous spectral range for a series of solar occultation observations.

As TGO goes into, or comes out of, the shadow of Mars, ACS MIR makes a series of observations of the sun while the limb of the atmosphere lies between the spacecraft and the sun. Spectra are obtained at unique tangent heights every 2–4 km. By comparing the observations through the atmosphere with those made above the atmosphere, we can determine how much sunlight was absorbed by the atmosphere along the line-of-sight (LOS). ACS MIR uses a 2D detector and the vertical field of view of the fore-optics allow $\sim$ 12 spectra to be acquired at each tangent height. By analyzing each of the detector rows and then taking the average of the retrieved mixing ratio vertical profiles, we can greatly improve the accuracy of our results and the sensitivity of the retrievals to trace gases, or low VMRs towards the limits of our sensitivity. Instrument details can be found in Korablev *et al.* (2018) and Trokhimovskiy *et al*. (2020).

Contemporary Mars Climate:

Mars' axial tilt is similar to Earth's, giving rise to similar spring, summer, fall, and winter seasons. The effects of these seasons are very visible in nadir-looking or column abundance measurements with near-surface cold and dry winters and warmer and more humid summers, with water vapour increasing towards the polar regions where the ice caps cycle through sublimation and freezing.

The atmosphere above the lowest scale height (~8 km) reveals a different picture. Spring and summer in the southern hemisphere coincide with Mars perihelion. The extra insolation creates a stronger seasonal sublimation cycle on the south polar cap, resulting in larger atmospheric pressures over this period. This leads to increased dust activity and atmospheric heating. We find that the upper atmosphere in the northern fall and winter is warmer and wetter than during northern spring and fall (Fedorova *et al*. 2020, 2023; Brines *et al*. 2023).

Using data from both ACS and MCS (Kleinböhl *et al*. 2009), Olsen *et al.* (2024a) and Olsen *et al*. (2024b) we show how the dust, temperature, water vapour and water ice interact with one another with altitude and over time. Seasonal heating, expansion of the lower atmosphere, and vertical transport faster than the rate of water ice freezing lead to periodic high altitude water vapour enhancements that may have led to more rapid hydrogen loss to space (Alday *et al.* 2021; Belyaev *et al.* 2021; Fedorova *et al.* 2020; Kleinböhl *et al.* 2024).

HCl and (no) Other Trace Gases on Mars:

HCl was detected in the Martian atmosphere for the first time using ACS data (Korablev *et al.* 2020; Olsen *et al.* 2021). It appeared following the 2018 global dust storm and its signal disappeared in the data at the end of the southern summer dusty period. Such rapid photochemical production and loss mechanisms are unknown, but a possible link to the freeze thaw cycle of water vapour, which HCl is correlated with, may be at play (Korablev *et al.* 2020; Olsen *et al.* 2021, 2024a, 2024b). While HCl is expected to be the long-lived reservoir species of chlorine, its rapid photolysis will eventually lead to ClO bond formation and eventual sedimentation to the surface (Catling *et al.* 2010).

The presence of HCl is therefore indicative of a contemporary chloride source in the atmosphere. These could include out-gassing from ancient magmatic reservoirs or recent chlorinated volcanic activity. There are ways in which surface minerals in suspended dust may be able to free chlorine using energetic processes, or mechanisms analogous to sea salt-HCl formation on Earth (see Korablev *et al.* 2021).

Other trace gases expected to be found at Mars have not yet been detected with TGO instruments. These include organic molecules, especially methane (CH_4; Knutsen *et al.* 2021; Montmessin *et al.* 2021), and sulfur-bearing molecules (Braude *et al.* 2021). Due to the previous reported detection of CH_4, its presence was expected (e.g., Giuranna *et al.* 2019; Webster *et al.* 2021), and a key driver of the ExoMars mission. Finding methane alongside other organic molecules would have been a hint towards a biogenic source. Finding it alongside sulfur and chlorine would hint at a geochemical source.

Similarly, had sulfur-bearing molecules such as H_2S or OCS been detected alongside HCl, it would have been a strong indication of contemporary magmatic activity. Finding HCl on its own has created a deep mystery we are continuing to investigate, while also continuing to search for CH_4, H_2S, OCS, and other trace gases indicative of active geological or biogenic processes, and critical to understanding the evolution of Mars and its atmosphere.

In this presentation, we will cover the ACS data and our interpretations of it and discuss the important aspects of chlorine chemistry for Martian climate, past and present.

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