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Maps of Martian Atmospheric H_2O with Trace Gas Orbiter's NOMAD/LNO

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1. Introduction

The Martian surface displays features such as dendritic channels that suggest it once had abundant flowing water on its surface. This picture is strongly contrasted with present day Mars, whose thin atmosphere and desiccated surface suggest a significant amount of water was lost to space or is being stored in sub-surface reservoirs. Martian atmospheric D/H and argon isotope analyses indicate Mars has lost an ocean of water from its surface [1] and more than 66% of its atmosphere [2]. Mapping the horizontal transport of fractionated atmospheric volatiles, such as H_2O and HDO suggests there is geographic and seasonal variability in the exchange of volatiles from differing reservoirs [3]. Here we present the first maps of H_2O water vapor as observed by the ExoMars Trace Gas Orbiter 2016 (TGO) over a period of 10 months and across several Martian seasons. These observations reveal geographic, diurnal, and seasonal variations which partially agree and partially challenge advanced global circulation models. Horizontal transport affects our interpretation of global maps or in-situ analysis (such as the Mars Science Laboratory) of fractionated species, such as D/H. These maps can be instrumental in improving our current understanding of the Martian water cycle and volatile transport.

2. Observations & Data Processing

Remote sensing of the Martian atmosphere permits observations at all altitudes, latitudes and longitudes, and over many seasons. The Nadir and Occultation for MArs Discovery (NOMAD) instrument is part of the payload of the Trace Gas Orbiter, an ESA/ROSCOSMOS joint mission to Mars. TGO's orbit observes the dayside of Mars at many local times and latitudes, unlike many of its polar orbiting predecessors. The NOMAD instrument observes the Martian atmosphere in solar occultation, limb, and nadir geometries [4]. With a two-hour orbital period, it makes two sets of solar occultations near the terminator at all latitudes and traces out surface tracks of atmospheric molecular species.

Since nominal science began in April 2018, NOMAD has conducted a spectroscopic survey of Mars' atmosphere in UV, visible and IR wavelengths covering the 0.2 - 0.65 and 2.3 - 4.3 μm spectral ranges. NOMAD is composed of 3 channels: a solar occultation only channel (SO) operating in the infrared wavelength domain, a second infrared channel capable of doing nadir, but also solar occultation and limb observations (LNO), and an ultraviolet/visible channel (UVIS) that can work in all observation modes. The spectral resolution of SO and LNO surpasses previous surveys in the infrared by more than one order of magnitude. NOMAD offers an integrated instrument combination of a flight-proven concept (SO is an updated and improved version of SOIR from Venus Express), and innovations based on existing and proven instrumentation (LNO is based on SOIR/VEX and UVIS has heritage from the Humboldt ExoMars lander), that will provide mapping and vertical profile information at high spatio-temporal resolution.

The three channels have each their own ILS and optical baseplate, but share the same single interface to the S/C. The optical layout of LNO is identical to that of SO using an echelle grating with a groove density of 4 lines/mm in a Littrow configuration in combination with an Acousto-Optic Tunable Filter (AOTF) for spectral window selection. The width of the selected spectral windows varies from 20 to 35 cm^{-1} depending on the selected diffraction order. The detector is an actively cooled HgCdTe Focal Plane Array. The LNO channel measures in the wavelength range between 2.3 and 3.8 μm, with a typical resolving power ($\lambda/\delta\lambda$) in the 10,000 to 15,000 range.

Observations with LNO are radiometrically calibrated using solar scans, and I/F ratios are then constructed for nadir observations. Three orders are predominantly used to retrieve water, orders 167, 168, and 169 (3754 - 3829 cm^{-1}). These absorption features are retrieved with state of the art radiative-transfer suite [5] which utilizes a priori atmospheric information from the Mars Climate Database (MCD [6]). This allows direct comparison with retrieved H_2O column abundances and model predictions. The surface albedo of Mars is characterized by CRISM observations, and interpolated to be appropriate for the spatial resolution of TGO. The radiative transfer is modelled by the Planetary and Universal Model of Atmospheric Scattering (PSG/PUMAS) [1], which computes layer by layer calculations along the line of sight for a variety of observing geometries, and is validated for Mars based on appropriate scattering models [7].

Data is arranged according to similar geophysical conditions, and where overlapping observations exist we employ a smoothing weighted average which considers the SNR of the observation appropriately. This allows the construction of maps of the Martian water cycle over relevant time scales, from local time variations to seasonal, and across the planet's daylit hemisphere.

3. Initial Results

The Martian year can be subdivided into six seasons (60° Ls each), rather than the four that is typically considered for Earth. Rather than considering spring or autumn as one season, it is appropriate to subdivide these time periods into early and late to capture the rapid changes in the Martian atmosphere that exist during these time periods. We report here on observations from Early Spring (ES) to Early Autumn (EA) in the southern hemisphere, which spans Solar Longitude 120 - 360°. At the time of submission, TGO data is processed until Feb 2019, but this is likely to be increased before the final submission of this manuscript.

LNO observations of the dayside of Mars must be constrained to less than 60° solar zenith angle to have reasonable signal to noise, but this still allows for a wide variety of sampled geophysical conditions. This dataset samples local times from ~7 to 17 hours, latitudes from 75S to 75N, and all longitudes. The geographic coverage from a given season is robust enough that the data may be separated into dawn, noon and dusk observations, allowing the Martian diurnal water cycle to be revealed.

The geographic distribution of water observed is consistent on some scales with the Mars Climate Database global circulation model, and differs in other significant ways. For example, during the Southern Summer time period, the GCM model results reproduce the geographic morphology of water vapor near the south pole, however, seem to miss an abundance of water that is associated with Hellas Basin, which increases throughout the day. In general, the models seem to overpredict the abundance of water, however this will need to be verified with modelers and intense scrutiny of the retrieval process simultaneously. However, there is good confidence in the retrieval process as verified by the SH Early Spring data, which shows very strong agreement at mid-latitudes. On the other hand, the GCM model results during this time period under-predicts the abundance of high latitude water, and overestimates the low latitude abundance, perhaps indicating incomplete horizontal volatile distribution.

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