1.0 Abstract

The Mars upper atmosphere is important for understanding the planet's climate evolution as well as serving as a laboratory for understanding processes in planetary atmospheres throughout the Universe. Over the past 5 years, the ESA Trace Gas Orbiter (TGO) and NASA Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter made contemporaneous measurements of the Mars upper atmosphere. When taken together, these missions can provide the most complete understanding of the Mars upper atmosphere ever realized. This study will be the first concerted attempt to combine the MAVEN and TGO observations and interpreting them on a global scale. The two goals of this proposed study are (1) to understand the structure and variability in the Mars upper atmosphere at a global-scale revealed in the MAVEN and TGO composite data, and (2) to compile the most comprehensive observational record of the neutral density and composition of the Mars upper atmosphere using MAVEN and TGO. These goals will be achieved by (1) comparing contemporaneous/simultaneous solar occultations measured by MAVEN/EUVM and TGO, (2) comparing composition and minor species measurements from MAVEN/NGIMS and TGO from the homopause to the exobase, (3) generating a composite dataset of atmospheric density and composition from the mesopause to the exobase and (4) analyzing the composite dataset's variations with latitude, local time and solar activity with the aid of general circulation models.

2.0 Scientific Rationale

2.1 Scientific Background

The Mars upper atmosphere is complex and distinct from that of Earth, and serves as a unique laboratory for studying atmospheric processes universal to all planets. Large scale circulation cells and small scale gravity waves, modulated by the dust cycle, input energy from below; while the solar irradiance and solar wind, modulated by the planet's highly eccentric solar orbit, input energy from above. These competing processes significantly influence the global and vertical structure of the Mars upper atmosphere. This region of the atmosphere serves as the reservoir for escaping neutrals and ions, which have been carried away by the solar wind for millennia, a process that continues today. As such, the composition, structure and variability of the Mars upper atmosphere provide insight into how the planet has evolved over time and the fate of vast quantities of liquid water that once flowed on the surface of Mars as is evident in the geological record.

Over the past 5 years, the ESA Trace Gas Orbiter (TGO) and NASA Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter made contemporaneous measurements of the Mars upper atmosphere. TGO and MAVEN have different science goals and are uniquely instrumented to achieve those goals. Thus, TGO and MAVEN observations are complementary and generally not redundant. ***When taken together, these missions can provide the most complete understanding of the Mars upper atmosphere ever realized***.

MAVEN began science operations in November of 2014. It includes instruments for observing the solar wind, solar extreme ultraviolet (EUV) irradiance, atmospheric plasma and atmospheric neutral species. This project will primarily focus on the atmospheric neutral measurements, although the plasma and space environment measurements will be used as needed to constrain solar drivers for variability observed in the neutral atmosphere. MAVEN observes the Martian neutral atmosphere with three instruments: the Neutral Gas and Ion Mass Spectrometer (NGIMS), the Imaging Ultraviolet Spectrograph (IUVS), and the Extreme Ultraviolet Monitor (EUVM).

NGIMS measures neutral composition and density *in situ* with a maximum altitude above 300 km and minimum altitude of ~150 km (~200 km) before (after) August 2020 when the orbit periapsis altitude was raised to conserve fuel. Additionally, NGIMS was able to sample down to ~120 km through a series of nine deep dip campaigns, when the spacecraft's periapsis altitude was lowered for approximately one week for each campaign. The deep dip campaigns were selected to sample a range of local times, latitudes, and seasons.

IUVS measures neutral composition and density remotely in primarily two different modes: airglow limb scans and stellar occultation. The airglow limb scans sense the atmosphere from ~80 km to ~160 km using a series of UV emission features and can measure the densities of neutral species on the dayside. The stellar occultations measure neutral species from below 90 km to 150 km on both the dayside and nightside of the planet.

EUVM measures neutral density from 120 km to 200 km with EUV solar occultations. The local times are inherently at the solar terminator (either dawn or dusk).

TGO started the science operation in April 2018. Its primary objective is the detection of trace gas and the study of their distributions. The spacecraft instruments are two spectrometers, one neutron detector, and a camera. The two spectrometers are the Atmospheric Chemistry Suite (ACS) and the Nadir and Occultation for MArs Discovery (NOMAD). Those spectrometers can measure spectral signatures of CO_2 from the lower atmosphere into the upper thermosphere, CO into the upper mesosphere, and H_2O into the upper mesosphere during southern summer. The spectrometers on TGO also monitor atmospheric dust, pressure, and temperature in the lower atmosphere. More work is required to understand the impact on the upper atmosphere of dust loading and the variability of other measured quantities in the lower atmosphere.

NOMAD is a suite of three spectrometers. Solar Occultation (SO), an infrared channel (covering wavelengths between 2.2 µm and 4.4 µm) dedicated to solar occultations; Limb, Nadir and Occultation (LNO), an infrared channel (2.2-3.8 µm) mainly dedicated to limb and nadir measurements; and Ultraviolet-Visible (UVIS), working in the 250-600 nm wavelength range and which performs solar occultations, limb, and nadir measurements. The LNO and UVIS channels monitor the lower atmosphere, while the SO channel measures the spectral signature of CO_2 into the upper thermosphere (~190 km) and scans the terminator of Mars. SO can also measure the spectral signature of CO into the upper mesosphere (100 km) and H_2O into the upper mesosphere during southern summer. The temperature is retrieved from the CO_2 spectral signature into the upper thermosphere.

ACS is a suite of three spectrometers: Thermal InfraRed channel in honor of professor Vassilii Ivanovich Moroz (TIRVIM), an infrared channel dedicated to SO and nadir measurements (covering wavelengths between 7.7 µm and16.1 µm), Near InfraRed (NIR), an infrared channel (0.7-1.7 µm), and Middle InfraRed (MIR), an infrared channel (2.3-4.3 µm) both dedicated to solar occultation measurements. In thermal IR, TIRVIM monitored the lower atmosphere (0-50 km) when nadir pointed, but when in the solar occultation configuration, all ACS channels (NIR, MIR and TIRVIM) can probe the upper atmosphere. NIR senses the CO_2 and H_2O densities, and the temperature into the upper mesosphere (0-100 km). MIR senses the H_2O density into the upper mesosphere and the CO_2 density and the temperature into the upper thermosphere (~190 km), TIRVIM derives the CO_2 density and temperature up to the thermosphere (~140-160 km).

The MAVEN and TGO observations are rarely co-located, thus providing a more global view of the Mars upper atmosphere when combined. This is useful for understanding atmospheric dynamics, where observations at a single location only tells part of the story. An example of this is thermospheric polar warming (TPW), where high altitude dust in the summer hemisphere, drives warming in the winter hemisphere. TPW has been observed in a number of studies, but simultaneous observations of the upper atmosphere in both hemispheres during TPW has never been attempted, yet it would reveal a more complete understanding of this phenomenon. Additional studies of dynamics enabled by multi-mission analysis include studying compositional changes that are tracers for dynamics, especially during dust storms, as well as gravity wave influences on thermospheric temperature.

2.2 Goals, Objectives and Outputs

Goal 1: Understand the structure and variability in the Mars upper atmosphere at a global-scale revealed in the MAVEN and TGO composite data.

Goal 2: Compile the most comprehensive observational record of the neutral density and composition of the Mars upper atmosphere using MAVEN and TGO.

Objective 1. Compare contemporaneous/simultaneous solar occultations measured by MAVEN EUVM and TGO and analyze observed differences for new insight.

Objective 2. Compare composition and minor species measurements from MAVEN NGIMS and TGO from the homo-pause to the exobase.

Objective 3. Determine factors used to scale the MAVEN and TGO datasets to each other to generate a composite dataset of atmospheric density and composition from the mesopause to the exobase.

Objective 4. Analyze the composite dataset's variations with latitude, local time and solar activity. Support the analysis with theoretical understanding, and global circulation models (GCMs) in particular.

Objective 5. Identify discrepancies between MAVEN and TGO observations and recommend observational targets for future missions.

2.2 Methodology

2.2.1 Objective 1 Methodology

Objective 1 will be achieved by comparing solar occultation measurements made by MAVEN EUVM and TGO NOMAD when they are observing the same volume of atmosphere at near the same time. This occurs when their observational lines of sight pass through the same altitude, latitude, and local time. This configuration occurs for about 10 days every 6 to 12 months and multiple coincident observations have been identified by the proposal team. ***These observations will serve as the bridge between the two missions***. The retrieved densities and temperatures will be compared to provide new insight. For example, the MAVEN EUVM measurements are expected to be more accurate at high altitudes while the TGO NOMAD measurements are expected to be more accurate at lower altitudes. The individual measurement retrievals for each instrument can be adjusted within known constraints to improve agreement across the entire altitude range.

2.2.2 Objective 2 Methodology

Relative abundances of available minor species will be incorporated into composite maps at fixed altitude or composite altitude profiles at fixed location as appropriate. These will be compared with global circulation model (GCM) results.

2.2.3 Objective 3 Methodology

The overlapping measurements from the TGO instruments will be compared and any average offsets or scale factors between the datasets will be determined. The same exercise will be completed for the MAVEN measurements. Finally, offsets or scaling factors will be found between the MAVEN/EUVM and the TGO/NOMAD measurements allowing all TGO and MAVEN upper atmospheric measurements to be put on the same calibration scale.

2.2.4 Objective 4 and 5 Methodology

The composite data will be analyzed, focusing on aspects that cannot be understood when looking at measurements from a single instrument. Areas of focus will include global scale compositional variations, dynamical processes such as TPW, and tides in different atmospheric regions (e.g., the mesopause and thermosphere) and gravity waves. Observations will be compared to GCM outputs. Unexplained discrepancies between instruments or measurement-model comparisons will be considered for recommendations for further study by future missions.

2.3 Scientific impact

This study will result in a significant scientific impact, leading to a more complete understanding of the Mars upper atmosphere and a composite dataset that future researchers can study for further progress. The comparison between the MAVEN and TGO datasets will therefore enable science beyond that accomplished during the work described here.

2.4 Timeliness

Now is the optimal time to complete this study for the following reasons: Both MAVEN and TGO have collected adequate data to complete the proposed work, spanning over two Mars years and half a solar cycle. The MAVEN and TGO missions are both in their extended missions, so continuity of the mission into the future is uncertain. Yet, at this moment, the mission teams remain intact and would be able to apply and build upon the findings of this proposed study.

2.5 Innovation

The MAVEN and TGO datasets are complementary as the MAVEN dataset covers mainly the upper atmosphere and the TGO dataset covers mainly the lower atmosphere with overlap between 90 and 190 km. Compiling those datasets will provide the most complete knowledge about key parameters of the atmosphere of Mars and their variations across the planet.

2.6 Feasibility

All the required datasets have already been derived. We need to gather a team of experts to compile the datasets as described above. The timeline is appropriate for a team of 12 to achieve the goals and objectives described above and a detailed plan has been assembled below.

2.7 Scientific Legacy

This study will be the first concerted attempt to combine the MAVEN and TGO observations and interpreting them on a global scale. The resulting paper(s) are likely to become important references for future researchers using the MAVEN and TGO data.

2.8 Science Related to Space Data

This project exclusively uses space data from MAVEN and TGO to advance the science of the Mars upper atmosphere.

3.0 Project Workplan

June 2023 - September 2023:	Compile database of contemporaneous MAVEN and TGO instrument observations and sort according to atmospheric parameter (temperature, density, composition), altitude, location and time.
October 2023-January 2024:	Establish scaling factors and offsets between instruments on the same orbiter (e.g. MAVEN NGIMS versus MAVEN IUVS).
February 2024: Bern Meeting #1 (1 week)	1. Compare the MAVEN EUVM and TGO solar occultations. 2. Analyze and interpret offsets between the inter-mission solar occultations measurements found in #1. 3. Analyze the database of contemporaneous observations and determine periods and regions of focus. Establish analysis priorities. 4. Present and discuss scaling factors and offsets found between instruments on same orbiter. 5. Form cross-mission, cross-disciplinary working groups to focus on areas of specialization (mesopause, thermosphere, tides, etc.)
March 2024-June 2024:	Compile additional data for focus periods (dust conditions, solar cycle, etc.). Establish scaling factors between MAVEN EUVM and TGO.
July 2024-August 2024:	Establish uniform scaling between TGO and MAVEN. Working groups prepare detailed tasks for Bern meeting.
September 2024: Bern Meeting #2 (1 week)	1. Merge data into composite dataset. 2. Working groups analyze composite dataset focusing on area of interest, report preliminary findings to full team. 3. Team determines science prioritization for publication.
October 2024-December 2024:	Formulate detailed outline for papers. Establish writing responsibilities.
January 2025-May 2025:	Write and submit papers of results.
June 2025	Write and submit final report to ISSI.

4. Expected Outputs

Output 1. A peer reviewed paper on the comparison of the contemporaneous and simultaneous solar occultations measured by MAVEN/EUVM and TGO.

Output 2. A peer reviewed paper on the analysis of the structure and variability of Mars atmosphere as revealed by the MAVEN and TGO composite dataset.

Output 3. Scaling factors to adjust the MAVEN and TGO datasets for future researchers to use for multi-mission analysis.

5. Financial Support Requested

We are requesting accommodations and per diem for two one-week visits in Bern for 12 named team members and up to 2 additional early-career researchers, totaling 24 person-weeks + 20%.