ON THE CONNECTION BETWEEN MARTIAN GRAVITY WAVES, DUST STORMS, AND ATMOSPHERIC ESCAPE.

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Introduction

Gravity waves play an important role in the dynamics and maintaining the thermal structure of all planetary atmospheres [*Yiğit and Medvedev*, 2019]. On Mars, they are generated in the lower atmosphere and propagate upward to the mesosphere and thermosphere, where they saturate and deposit their energy and momentum to the mean flow. Here, we present recent progress in the observation of upper atmospheric effects of gravity waves, focusing on observations provided by the NGIMS instrument onboard NASA's MAVEN spacecraft.

Thermospheric gravity waves during dust storms

Gravity waves continuosly propagate from the lower atmosphere to the thermosphere. Since global dust storms significantly change the large-scale dynamical and thermal structure, especially, of the lower atmosphere, it is expected that the generation, propagation, and dissipation of gravity waves are influenced by dust storms. Retrievals of gravity wave activity between 20-30 km from the Mars Climate Sounder (MCS) on board Mars Reconnaissance Orbiter (MRO) suggested that the gravity wave activity decreases during dust storms [*Heavens et al.*, 2020]. High-resolution Martian general circulation modeling showed that gravity wave activity actually increases in the upper mesosphere by up to a factor of two [*Kuroda et al.*, 2020]. More recently, retrievals of gravity wave activity from density measurements by NGIMS/MAVEN showed that the GW activity increased by at least a factor of two in the Martian thermosphere as shown in Figure 1 (as adapted from the work of *Yiğit et al.* [2021]). The relative density fluctuations produced by gravity waves increased from 14-16% before the onset of the storm on 1 June 2018 up to 40% during the peak phase of the storm.

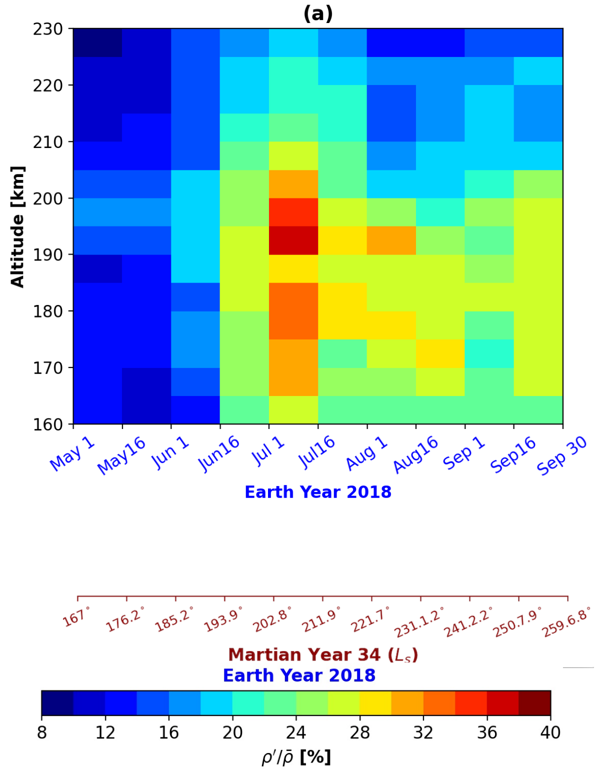

Figure 1: Variation of thermospheric gravity waves activity during the 2018 planet-encircling dust storm.

Thermospheric gravity waves at solar minimum

MAVEN has been observing the upper atmosphere of Mars since late-2014 to present. The latter part of the mission covers the most recent solar minimum, which provides an unprecedented opportunity to characterize the Martian gravity wave activity for the first time during low solar irradiation. Previous studies on Earth had suggested that GW activity is stronger during solar minimum than solar maximum [*Yiğit and Medvedev*, 2010]. On Mars, *Yiğit et al.* [2021] have conducted an extensive analysis of gravity wave activity during the last

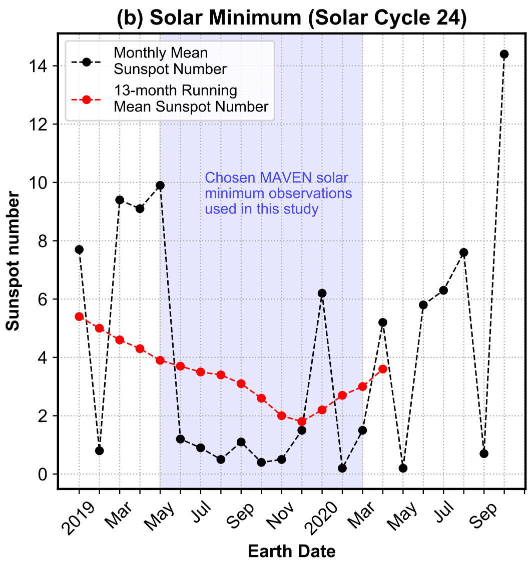

Figure 2: Variation of sunspots during the minimum of the Solar Cycle 24. The temporal range of the chosen MAVEN data set to analyze thermospheric GW activity is shown. [*Yiğit et al.*, 2021, Figure 1].

solar minimum. Figure 2 shows the sunspot number variations in 2019-2020 period and the temporal range of the MAVEN dataset used, which includes the solar

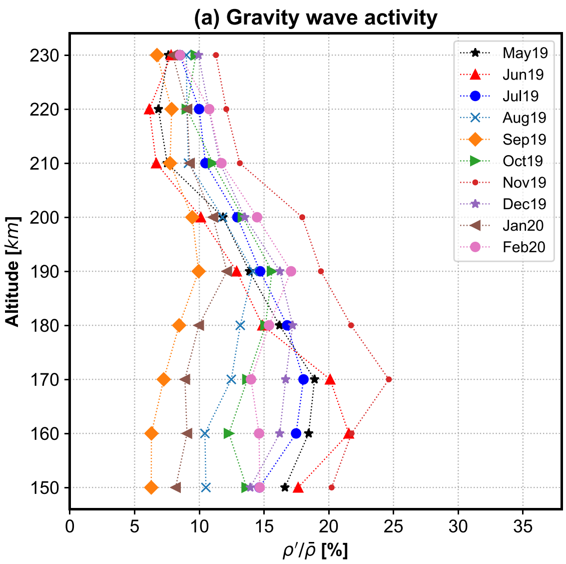

Figure 3: Variation of thermospheric gravity wave activity during the solar minimum from May 2019 to February 2020. Montly averages of relative density fluctuations due to gravity wave variations are shown [*Yiğit et al.*, 2021, Figure 4a]

minimum. It is seen that the 13-month running mean

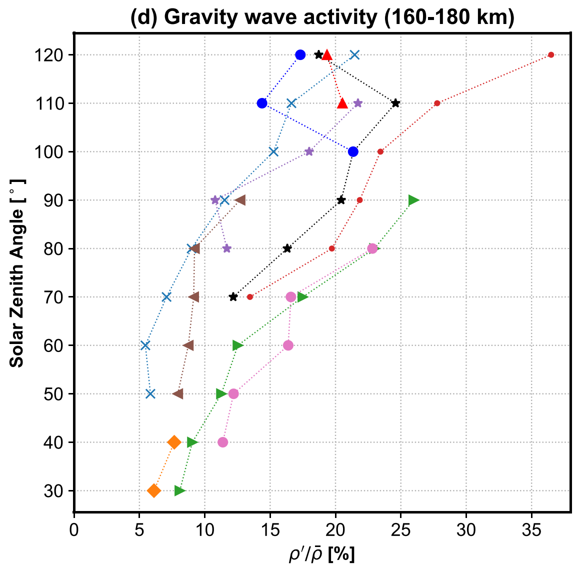

Figure 4: Solar zenith angle variation of thermospheric gravity wave activity during the solar minimum from May 2019 to February 2020. Montly averages of relative density fluctuations due to gravity wave variations are shown. See the legend in Figure 3 [*Yiğit et al.*, 2021, Figure 4a]

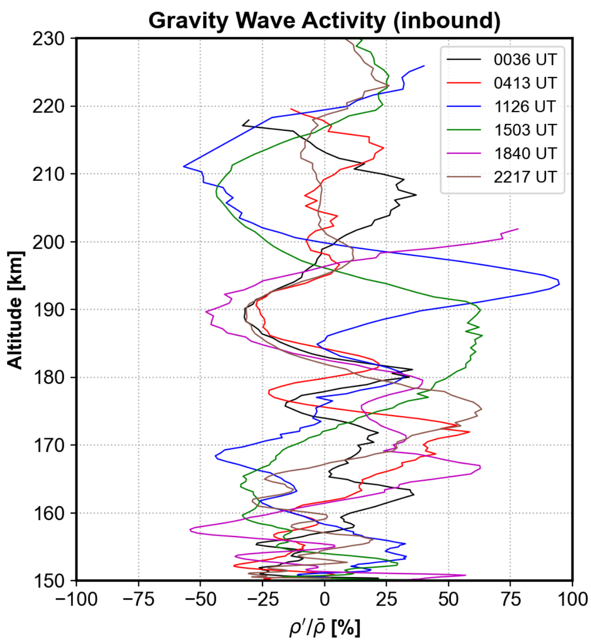

Figure 5: Variation of ing the solar minimum from May 2019 to February 2020. Montly averages of relative density fluctuations due to gravity wave variations are shown [*Yiğit et al.*, 2021, Figure 4a]

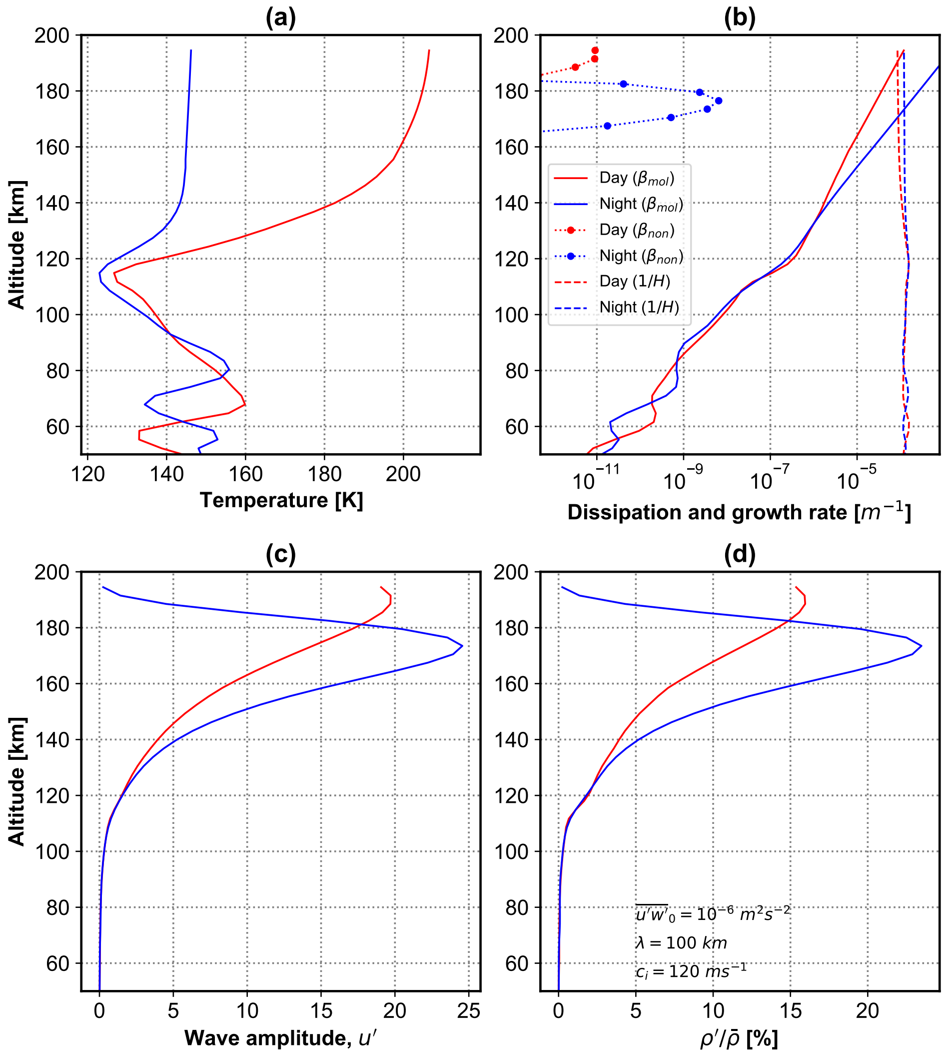

Figure 6: Gravity wave activity at night and day as simulated by a column model based on the whole atmosphere gravity wave parameterization of *Yiğit et al.* [2008] [*Yiğit et al.*, 2021, Figure 11]

sunspot number reaches a minimum in December 2019. They have studied the montly mean GW activity during the solar minimum as a function of altitude, latitude, local time, and solar zenith angle . Figure 3 presents the altitude variation of the gravity wave-induced relative density fluctuations as retrieved from the NGIMS instrument on board MAVEN. Gravity wave activity typically peaks around 160-190 km but varies from month to month between 5-25%. Figure 4 shows the solar zenith angle variations of the monthly mean gravity wave activity. Increasing gravity wave activity with increasing solar zenith angle suggests that the nighttime gravity wave activity is greater than the daytime one. Figure 5 shows gravity wave induced density fluctuations for six consecutive MAVEN orbits on 5 December 2019. Instantaneously GW activity can reach up to 100% with significant degree of orbit-to-orbit variations, depending on the altitude. During 5 December 2019, mainly the longitude varies while the other orbital parameters, such as latitude and local time do not vary much between the different orbits. Hence, these variations indicate the presence of longitudinal variability in thermospheric GW activity. Overall, these results highlight the variable nature of gravity wave propagation and dissipation processes in the thermosphere.

The day-night difference in gravity wave activity

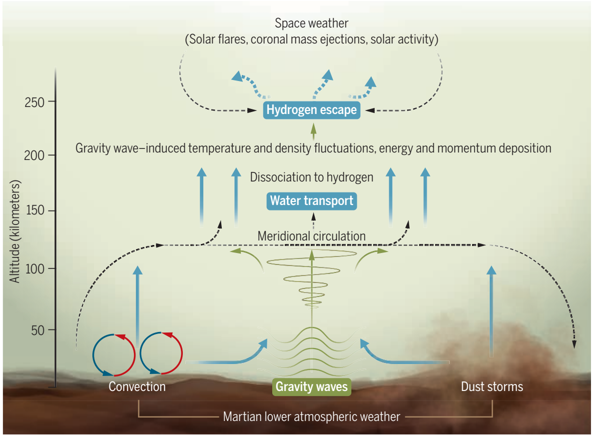

Figure 7: Illustration of the connection between dust storms, atmospheric gravity waves, and escape of hydrogen from the Martian upper atmosphere [*Yiğit*, 2021].

shown in Figure 4 is worth revisiting. In order to study how the gravity wave activity varies as a local time, *Yiğit et al.* [2021] conducted column model simulations using the whole atmosphere gravity wave parameterization of *Yiğit et al.* [2008]. Figure 6 presents the altitude variations of temperature, gravity wave dissipation rate, amplitude, and relative density fluctuations for representative daytime and nighttime. It is seen that that the nighttime wave amplitude growth rate exceeds the daytime growth rate in the thermosphere, while the dissipation at nighttime due to molecular viscosity is greater than the dissipation during daytime, however, the growth rates exceed the dissipation rates up to 170 km. The ultimate effect of these differences between the growth and dissipation during day and night lead to stronger nighttime gravity wave activity.

Gravity waves and atmospheric escape

Influence of gravity waves on atmospheric escape is a long-range multi-step process. So far there is a significant degree of evidence not only for the dynamical importance of gravity wave in the thermosphere, but also for a potential role of gravity waves in atmospheric escape on Mars. Figure 7 illustrates how lower atmospheric gravity waves can modulate loss of water on Mars, as adapted from the work by *Yiğit* [2021]. When gravity waves dissipate in the upper atmosphere, they can alter the mean meridional circulation, which can modulate the upward transport of water into the thermosphere, to the regions where it can be dissociated into its constituents, hydrogen and hydroxl. Recent general circulation modeling studies have provided evidence for this mechanism [*Shaposhnikov et al.*, 2022]. Hydrogen can then easily escape to space via Jeans' escape mechanism.

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