Nightside wave perturbations in the Martian thermosphere

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Although there have been very limited observations in the Martian thermosphere, especially on the night side, our understanding of the region has been rapidly enhanced in recent years by the MAVEN spacecraft (Bougher et al. (2015) ; Yigit et al. (2015) ; England et al; Siddle et al. (2019) ; Nakagawa et al. (2020) Recent observations have reported that wave-like perturbations are ubiquitously observed in the thermosphere, especially on the night side, with large amplitude density perturbations exceeding 50%. The anti-correlated amplitudes with the background temperature suggest the saturated atmospheric gravity wave (Terada et al., 2017). There are two possible excitation sources: (1) atmospheric gravity waves propagating upward from the lower atmosphere, and (2) energy injected from the upper atmosphere by external factors such as solar wind or energetic solar particles.

The widespread diffuse aurora on Mars (Schneider et al., 2015, 2020), recently discovered by the MAVEN spacecraft, is a luminous phenomenon that covers the entire Martian night side with the arrival of solar energetic particles (SEPs) and has an emission altitude of 60 km. This suggests that energetic particles can have a significant impact on the deep Martian atmosphere by globally injecting energy. In particular, ionization, dissociation, heating, and disturbance effects in the upper atmosphere can potentially have an impact on the escaping atmosphere, and are important for understanding the response of Mars, a non-magnetic planet, to space environment changes.

In this study, we use the MAVEN onboard mass spectrometer NGIMS to reveal the long-term interannual variation of density perturbation components in the

Martian thermosphere. In particular, NGIMS has realized the multi-molecular observation since Viking, and here we focus on the difference in behavior between CO_2 and N_2 density perturbations in order to constrain the excitation source. In this study, we used the MAVEN/NGIMS data Level-2 and version-8 registered in NASA PDS.

In the evolution of the CO_2 density disturbance components over the five-year period from 2015 to 2020, we find that the amplitude of the density perturbations is significantly larger in the nighttime than in the daytime throughout the five-year period. This is consistent with the results of recent previous studies (Terada et al., 2017; Nakagawa et al., 2020). On the other hand, it should be noted that the amplitude of the density disturbance differs from year to year. In this paper, we will discuss in detail the relative importance of the lower and external factors on the interannual variation. Another important feature is the relationship between the perturbation amplitude components of CO_2 and N_2. The statistical results show that the two are basically well correlated, with CO_2 of a larger perturbation amplitude than N_2. This is consistent with the arguments of Cui et al. (2014) and England et al. (2016, 2017), because the disturbance amplitude normalized by the background density is anti-correlated to the scale height, and the amplitude ratio corresponds to the mass ratio of the molecular species. In fact, a scatter plot of the disturbance amplitudes of CO_2 and N_2 shows a distribution that follows with a mass ratio of $28/44 \sim 0.64$, the mass ratio of CO_2 and N_2. Analysis of the perturbation components for each orbit shows that CO_2 and N_2 are well in phase with each other in many cases. On the other hand, we also find the N_2 perturbation amplitude sometimes exceeds that of CO_2, meanwhile the perturbations seen in N_2 appear to be out of phase with those in CO_2. Interestingly, according to the predictions of the full-particle Direct Simulation Monte-Carlo (DSMC) modeling of the Martian upper atmosphere (Terada et al., 2016), the atmospheric waves excited at thermospheric altitudes during the injection of energetic particles from space have different wavelengths and amplitudes at each species. It is suggested that the amplitude of N_2 perturbations exceeds that of CO_2 at the distance from the source region (Terada et al., in prep.). In this paper, we compare and discuss the predictions with this numerical model and the implications of the observations.

これまで火星熱圏、特に夜側での観測事例は極めて限定的であったが、MAVEN探査機によって近年理解が急激に進んだ。Bougher et al. (2015) ; Yigit et al. (2015) ; England et al. (2017) ; Terada et al. (2017) ; Siddle et al. (2019) ; Nakagawa et al. (2020)によって、波状擾乱成分が熱圏で定常的に観測されており、特に夜側で 50%を超える大振幅の密度擾乱が報告されている。背景温度場と反相関であることから飽和した大気重力波であることが示唆されている（Terada et al., 2017)。考えうる励起源の可能性は、(1)下層大気で励起された大気重力波が上方伝搬したもの、(2)太陽風や太陽高エネルギー粒子など外的要因により上部から注入されたエネルギーにより励起されたのの、の 2 つが考えられるが、その励起源は未だ明らかでない。
近年、MAVEN 探査機によって発見された新しい火星オーロラ（Schneider et al., 2015, 2020）は、太陽高エネルギー粒子 SEP 到来に伴って火星夜側全球を覆う発光現象でありその発光高度が 60km におよぶことから、宇宙環境変動が火星大気深部へエネルギーを全球的に注入し大きな影響を及ぼしうることを示唆した。特に、大気散逸のリザーバである超高層大気における SEP による電離・解離・加熱・擾乱効果は、大気散逸へも影響を及ぼしうることから興味深く、非磁化惑星である火星の宇宙環境変動応答の理解に重要である。
本研究では、MAVEN 搭載質量分析器 NGIMS を用いることで、火星熱圏でみられる密度擾乱成分の長期間年々変化を明らかにすることを目的とする。特に、NGIMS は Viking 以来となる多分子観測を実現しており、ここでは CO_2 密度擾乱と N_2 密度擾乱の振る舞いの違いに着目し、励起源の制約を試みる。本研究では NASA PDS に登録されている公開 NGIMS データ Level-2、version-8 を用いた。
2015 年から 2020 年に及ぶ 5 年間の CO_2 密度擾乱成分の変遷に着目すると、5 年間通じて昼側よりも夜側で密度擾乱振幅が顕著に大きいことがわかる。これは近年の先行研究結果と合致する（Terada et al., 2017; Nakagawa et al., 2020)。一方で、年毎にその密度擾乱振幅に違いがみられることにも着目する。本書では、年々変化に対する下側要因・外的要因それぞれとの因果関係を詳しく議論する。もう一つの大きな特徴は、CO_2 と N_2 の擾乱振幅成分の関係である。統計的な結果を見ると、双方は基本的に相関がよく、CO_2 の方が N_2 よりも擾乱振幅が

大きい傾向を示す。これは Cui et al. (2014)および England et al. (2016, 2017)の結果と合致し、背景密度で規格化された擾乱振幅がスケールハイトに反比例することから、振幅比は分子種の質量比と対応するためである。実際、CO_2とN_2の擾乱振幅の散布図を作成すると、CO_2とN_2の質量比である 28/44 ~ 0.64 の直線にほぼ従った分布を示す。軌道毎の擾乱成分を分析すると、CO_2とN_2は位相が非常によく合っているケースが多く見られる。一方で、N_2擾乱振幅がCO_2のそれを上回るケースや位相が合わないケースも存在していることがわかる。大変興味深いことに、我々の火星大気全粒子 Direct Simulation Monte-Carlo (DSMC)モデリング（Terada et al., 2016）の予測によれば、降り込み粒子を注入した際に熱圏高度で励起された大気波動は、分子種によって波長・振幅が異なり、ソース領域から離れるに従って、N_2擾乱振幅がCO_2のそれを上回るケースが存在しうることを示唆している（Terada et al., in prep.）。本書では、この数値モデルとの予測と観測から得られた示唆について比較し考察する。

P16 2/17 C班 15:00-15:30

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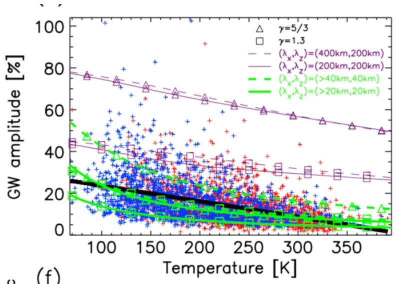
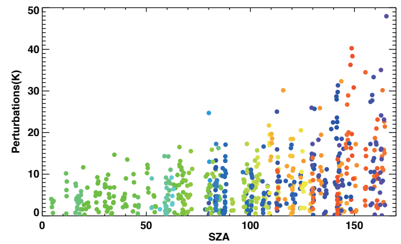
Introduction

- Wavelike perturbations are ubiquitously observed especially on the nightside with large amplitudes (>50%)
- Possible excitation sources: (i) atmospheric gravity waves from below, and (ii) energy injected from above



Terada et al., 2017



Nakagawa et al., 2020

Purpose

- MAVEN/NGIMS (in-situ mass spectrometer) to reveal the long-term annual variation of density perturbations in the Martian thermosphere.
- We focus on the different in behavior between CO_2 and N_2 density perturbations in order to constrain the excitation source.

Data *MAVEN/NGIMS*

- NASA PDS level-2, version-8
- Multi-molecular observations since Viking from 2015 for >5 years.
- Forth-order polynomial fit is applied to extract the perturbations.
- CO_2 and N_2 perturbations are basically well correlated in phase.

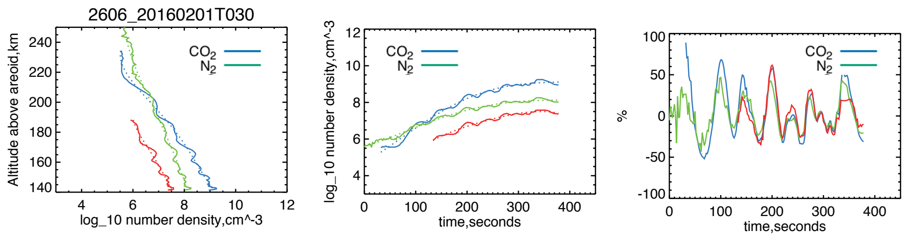


Fig. An example of the density profiles of CO2, N2, and Ar by MAVEN/NGIMS.

Result *Annual variation*

- Larger amplitudes on the nightside through the mission.
- Note the annual variation of amplitudes from year to year.

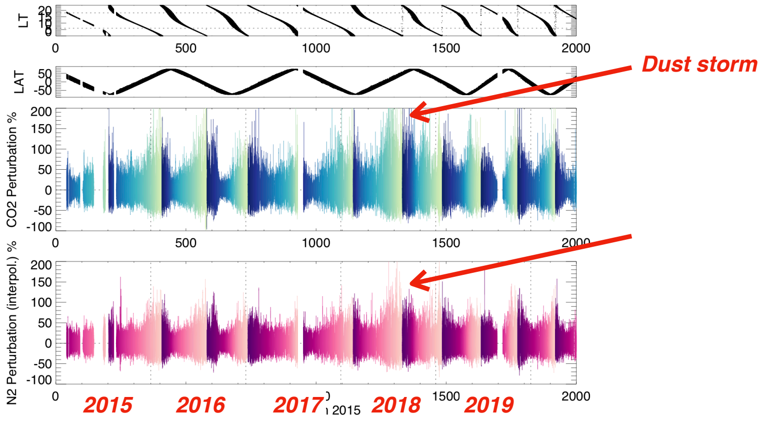


Fig. Annual variations of the CO2 and N2 density perturbations.

Result *Correlation*

- Statistical analysis show CO_2 and N_2 perturbations are well correlated, which is consistent with Cui+14 and England+16,17.
- The disturbance amplitudes normalized by the background density is anti-correlated to ***H***, so that ratio corresponds to M_{CO2}/M_{N2},~0.64.

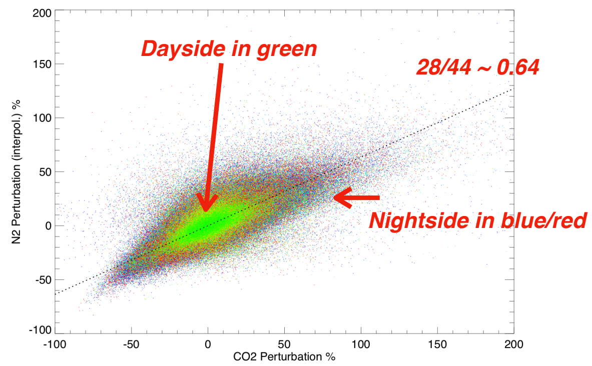


Fig. Correlation between CO2 and N2 density perturbations.

Result *Out-of-Phase*

- It is noteworthy that the N_2 perturbation amplitudes sometimes exceeds those of CO_2, while the N_2 perturbations seem to be out of phase with those in CO_2.

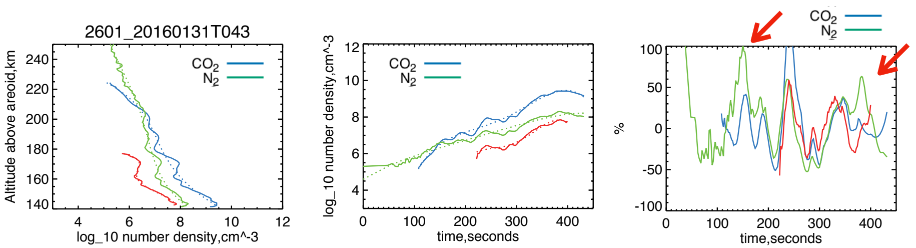
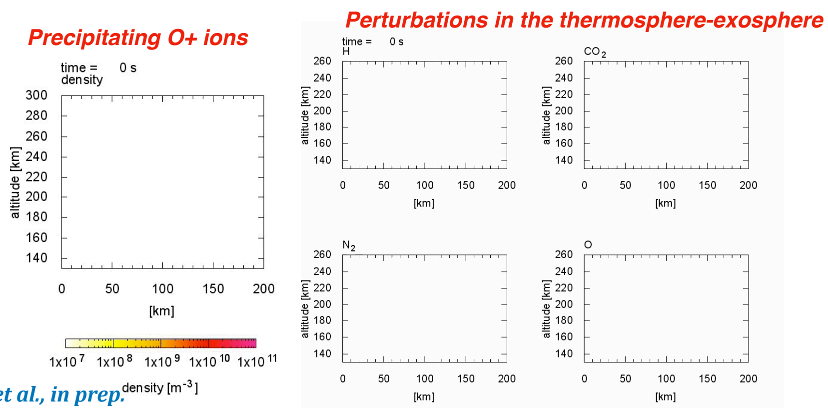


Fig. An example of the density profiles of CO2, N2, and Ar by MAVEN/NGIMS.

Discussion *DSMC prediction*

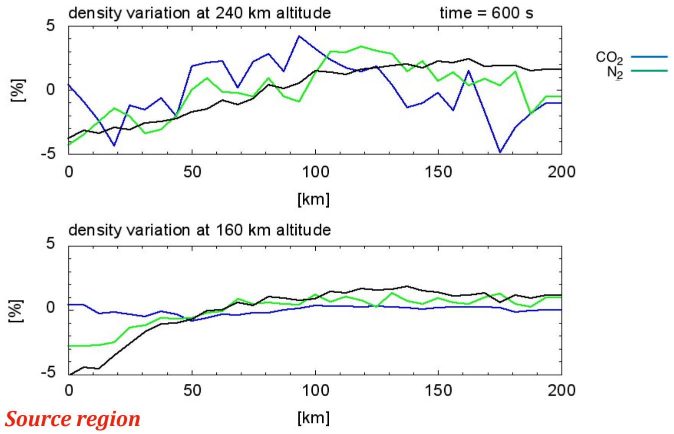
- According to the predictions of the full-particle Direct Simulation Monte-Carlo (DSMC) modeling of the Martian upper atmosphere (Terada et al., 2016), the density perturbations during the injection of energetic particles from space have different wavelengths and amplitudes at each species.



Terada et al., in prep.

Discussion *DSMC prediction*

- N_2 perturbations exceeds CO_2 at the distance from the source region (Terada et al., in prep.).



Terada et al., in prep.

Summary

- MAVEN/NGIMS observations suggest larger amplitude density perturbations exceeding 50% in the nightside throughout 5 years.
- Our result implies annual variation of the perturbations from year to year, which might be affected from below and/or above.
- CO_2 and N_2 density perturbations are statistically well correlated, following the mass ratio of the species, as suggested by previous studies.
- It is noteworthy that N_2 perturbations in some cases exceeds those of CO_2, to be out of phase for each other.
- DSMC simulations predict (1) N_2 amplitudes is larger than CO_2 away from the source region, (2) Even more, a very large precipitating flux of O+ ions is required. (Terada et al., in prep.)
- Further investigation is needed to identify the sources.