Thermal Tides in the Martian Lower Atmosphere observed by EMM/EMIRS.

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Introduction

Thermal tides|planet-wide atmospheric oscillations driven by the diurnal cycle of solar heating|are a dominant dynamical force in the Martian atmosphere, exerting first-order control on its weather and climate [2, 4, 5]. These waves include Sun-synchronous migrating tides, a direct response to solar forcing, and more complex non-migrating tides (NMTs) that arise from asymmetric heating and non-linear wave interactions [2]. The intricate interplay between these components defines the rich spectrum of Martian atmospheric variability.

Historically, our understanding of this full tidal spectrum has been severely constrained. Pivotal missions like the Mars Global Surveyor (MGS) and Mars Reconnaissance Orbiter (MRO) operated in Sun-synchronous orbits, whose limited local-time sampling introduced a strong observational aliasing that made it impossible to unambiguously separate different tidal components [7, 9, 10, 6]. Consequently, the true structure and variability of many tides, particularly the elusive NMTs in the dynamically crucial lower atmosphere, remained poorly resolved.

The Emirates Mars Mission (EMM) presents a paradigm shift. Its unique, high-altitude orbit enables the EMIRS instrument to achieve complete, uniform coverage of all geographic locations and local times within a short 10-sol period, effectively eliminating the aliasing that constrained previous studies[1, 8, 3].

This work leverages this revolutionary, alias-free dataset to conduct the first comprehensive investigation of the full spectrum of thermal tides over an entire Martian year. Our motivation is twofold: first, to establish a definitive climatology of migrating tides to test fundamental theories about their interaction with the background atmosphere; and second, to systematically dissect the non-migrating components to uncover their structures, excitation mechanisms, and novel wave phenomena previously hidden by observational limitations. By addressing both tidal types in a unified framework, we aim to provide a holistic view of how these waves govern the Martian climate system.

Results

Leveraging the unique orbital design of the Emirates Mars Mission (EMM) shown in Figure 1, our investigation utilizes the first-ever alias-free dataset from the EMIRS instrument to resolve the full spectrum of Martian thermal tides with unprecedented clarity, overcoming the historical limitations of fixed local-time observations. The complete and continuous local time sampling achieved over an entire Martian year, confirmed in Figure 2 (top panel), provides a robust foundation for our analysis.

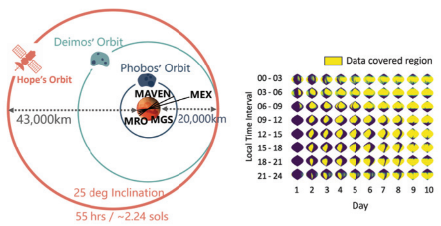

Figure 1: Schematic Diagram of the Hope Mission's Orbital Observations

We first examined the dominant migrating thermal tides to validate both our methodology and modern tidal theory. As showcased in the subsequent panels of Figure 2, the bottom-left panels display the clean, unambiguous structure of the diurnal temperature anomaly derived from our observations. It is noteworthy that while the observed anomalies are stronger than those from the model simulations after applying the EMIRS vertical convolution kernel, their wave-like patterns and phase structures are highly consistent. Most significantly, the bottom-center panel reveals a powerful confirmation of theory: the seasonal evolution of the diurnal tide (DW1) amplitude does not peak at the geographic equator. Instead, its maximum amplitude closely follows the "dynamical equator"|the latitude of zero potential vorticity, which migrates seasonally under the influence of the general circulation. This provides the first direct, global-scale observational evidence for this sophisticated interaction between tides and background winds. In parallel, the bottom-right panel reveals that the amplitude of the semi-diurnal tide (SW2) is strongly correlated with atmospheric dust loading, with its peaks coinciding with major dust storm seasons. This strong agreement with the latest Mars Planetary Climate Model (PCM) establishes high confidence in both our observational analysis and the model's physical framework.

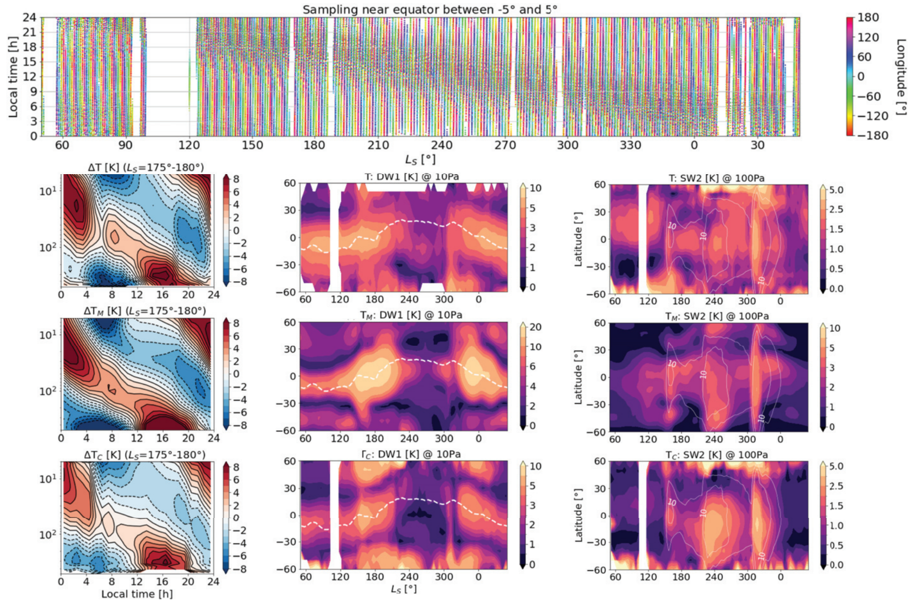

Figure 2: Orbital Sampling Characteristics of EMM/EMIRS; Diurnal Temperature Anomalies from EMM/EMIRS and Comparison of DW1 and SW2 Components with Model Simulations

This solid foundation enables an exploration of phenomena that were previously obscured by aliasing. Our comprehensive analysis has led to the first unambiguous identification of a previously unobserved non-migrating tide in the lower atmosphere: the terdiurnal, westward-propagating wavenumber-1 tide, which we designate as TW1. While this mode is relatively weak during clear atmospheric conditions, it undergoes a dramatic amplification during periods of high dust activity, with its amplitude exceeding 1 K during the Mars Year 36 C-class dust storm. This indicates that TW1 is not a minor feature but a significant component of Mars's storm-time dynamics, whose contribution to the atmospheric energy budget has been previously overlooked.

Beyond the discovery of new tidal modes, our data reveals novel wave dynamics, and Figure 3 presents compelling evidence for one such phenomenon: partial tidal wave reflection in the dusty troposphere. During the C-storm period, the vertical structure of the migrating DW3 tide deviates significantly from its expected monotonic growth. Instead, it exhibits a distinct amplitude nodela localized minimum in wave energylaccompanied by a sharp, 180-degree phase shear directly above it. This pattern is the classic signature of wave interference, which we interpret as the upward-propagating incident tide being partially reflected downward by a sharp vertical gradient in the atmospheric background state. Such a gradient is likely induced by the strong thermal and density contrasts associated with the top of the dense dust layer. This is the first time such a wave reflection process has been directly observed in the Martian troposphere, revealing a critical, previously under-appreciated feedback mechanism between dust-induced atmospheric structuring and global-scale wave propagation.

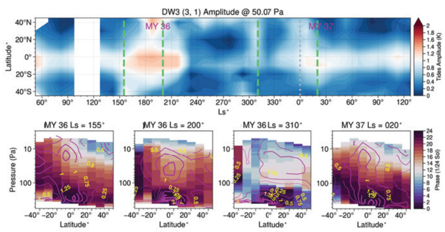

Figure 3: Seasonal Distribution of DW3 Amplitude Observed by EMM/EMIRS and Latitude–Altitude Structures of Amplitude and Phase During Different Solar Longitudes

Summary

This study uses full local-time coverage, alias-free EMM/EMIRS observations to investigate the full spectrum of Martian thermal tides. Our analysis validates modern theory, demonstrating the diurnal tide (DW1) follows the wind-driven "dynamical equator" and the semi-diurnal tide (SW2) is strongly modulated by dust. Building on this, we report two key discoveries previously obscured by aliasing. We present the first unambiguous identification of a new non-migrating tide, TW1, a significant component of storm-time dynamics. We also provide the first direct evidence of partial tidal wave reflection in the troposphere, linked to dust-induced atmospheric structuring. In conclusion, our work demonstrates that dust modulates the climate system not only via radiative heating but also through more complex pathways, such as generating new tidal modes and altering wave propagation. These findings reveal a more intricate Martian climate and provide critical constraints for future models.

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