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## Migrating Thermal Tides in the Martian Atmosphere from TIRVIM-ACS onboard TGO

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### Introduction:

Between March 2018 and December 2019, millions of spectra of Mars' surface and atmosphere thermal emission have been recorded in nadir geometry by TIRVIM/ACS, a thermal infrared spectrometer onboard the ExoMars Trace Gas Orbiter (TGO) [7]. From this wealth of data, we characterized in detail the thermal structure of the Martian lower atmosphere at a great variety of local times. Here we focus on the study of migrating thermal tides derived from TIRVIM observations, including during the Global Dust Event of MY34.

### Observations and Methods:

We have developed an algorithm coupling line-by-line radiative transfer and optimal estimation theory to retrieve the surface temperature, the vertical profiles of the temperature between a few km and 50-55 km (2-3 Pa), and the integrated optical depth of dust and water ice clouds [3]. The retrieved temperature profiles have a vertical resolution of 10 km in the lower atmosphere and a coarser resolution of 15-20 km in the range 2-20 Pa. They were validated against thousands of co-located observations from the Mars Climate Sounder, acquired in limb viewing geometry [3].

### Thermal structure and tides:

Thermal tides are planetary-scale oscillations resulting from the diurnal solar forcing of the thin Martian atmosphere. Migrating tides describe sun-synchronous modes propagating westward with the sun. The diurnal mode has one maximum and one minimum per day and a zonal wavenumber of one; the semi-diurnal mode has two maxima and two minima per day and a zonal wavenumber of two; etc. One of the main advantage of TGO's orbit is that the local time of TIRVIM nadir observations drifts by 13 minutes earlier each sol. After 54 sols, or 25-35° of Ls, a full coverage of the daily cycle is achieved, allowing to separate between diurnal and seasonal temperature variations. This is clearly an asset to study thermal tides compared to previous studies, mostly based on 2-4 AM and 2-4 PM temperatures obtained from sun-synchronous orbiters [1,4,6,9].

An example of the zonally-averaged temperature retrieved from TIRVIM at 30 Pa in the period March 13 - April 28, 2018 ( $L_s \sim 150^\circ$  of MY34) is shown below, as a function of latitude and local time. At the equator, the temperature is found maximum near 3~AM and minimum near 7~PM. This feature of warm nighttime temperatures at this altitude is well known and is a manifestation of the diurnal thermal tide [8]. The fact that these two temperature extrema are not separated by 12 hours is a first hint that the thermal field is also influenced by a semi-diurnal tide.

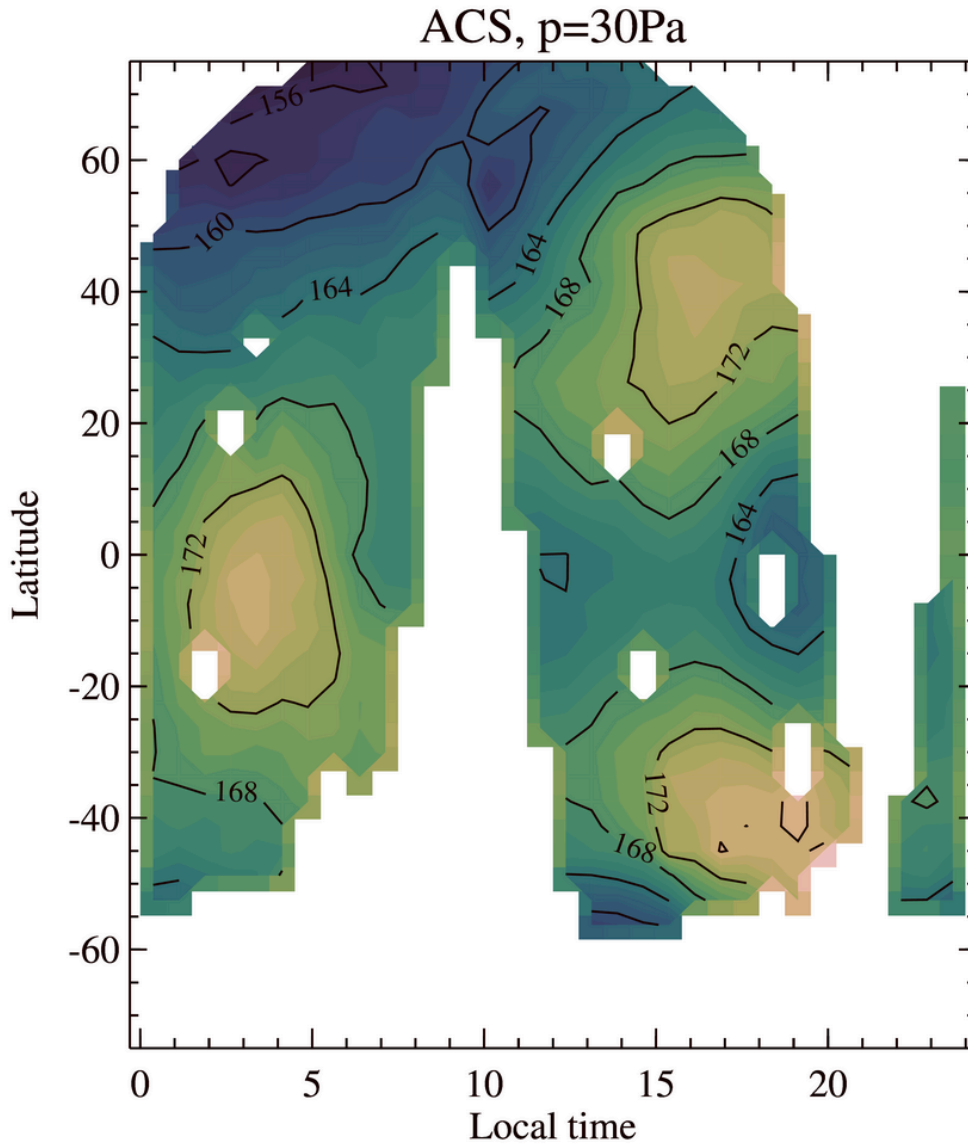


Figure 1: Zonally-averaged temperature retrieved from TIRVIM/ACS at 30 Pa, with latitude and local time. This figure gathers 45 sols of data around  $L_s \sim 150^\circ$ , MY34.

To study migrating tides qualitatively, we consider the zonally-averaged temperature in a fixed local time reference frame, in which other types of wave signatures (stationary waves, non-migrating tides,...) are averaged out. Following [6], we decompose the observed zonally-averaged temperature into a daily-averaged temperature plus sinusoidal functions at diurnal, semi-diurnal and ter-diurnal frequencies. We obtain the amplitude and phase of the migrating tides at each pressure level and

10°-wide latitudinal bin (see below an example of fits).

An amplitude of 4K is found for the diurnal mode near the equator, which decreases to 2K near 20°, and increases to 6K near 50°N. Very similar results are found at  $L_s \sim 90^\circ$  for MY35 [2]. We employ the same methodology to derive tides characteristics simulated in the LMD GCM. Temperature profiles from the model are extracted at the same locations and times as TIRVIM observations and are smoothed vertically using the appropriate averaging kernel matrix. The modeled tides exhibit very similar characteristics as those observed, except for a 1 to 2 hours phase shift; temperature extrema occurring at later local times in the model.

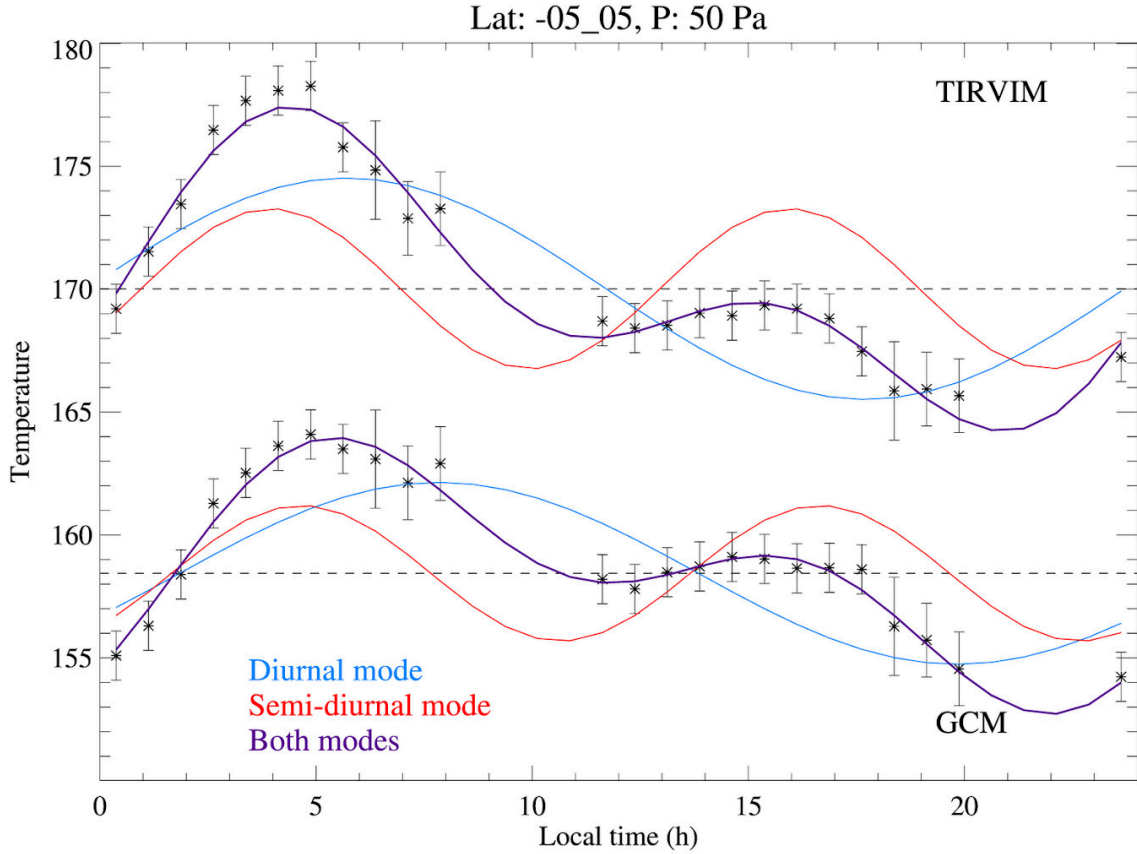


Figure 2: Fit (purple) to TIRVIM equatorial temperatures at 50 Pa (black stars, upper part) as a function of local time. It combines a daily average temperature (horizontal dashed line), diurnal and semi-diurnal signals, as labeled. The bottom part shows the same for GCM outputs (shifted by -15K).

One caveat is that even small seasonal variations over a martian month can hamper our analysis when characterizing the semi-diurnal tide [2]. To overcome this issue, we de-trend the data for seasonal variations using MCS observations. The derived amplitude of the semi-diurnal tide near the equator at  $L_s = 150^\circ$  ranges from 2K (at 100 Pa) to 6K (at 2 Pa), confirming that this tide mode is significant even in non-dusty seasons [6].

**Impact of the MY34 GDE:** A Global Dust Event started locally on 2 June 2018 and became planet-encircling on 21 June [5]. Compared to pre-storm conditions, we find that the diurnal tide amplitude strongly increases, reaching 32K at 50-60°S and 20K at 50-60°N at 50 Pa, while it remains unchanged ( $\sim 4$ K) near the equator. The semi-diurnal mode increases slightly (6-8K at 30-50 Pa, equator), while the ter-diurnal mode is also detected (amplitude of 5K near 50 Pa, equator). GCM simulations run with the MY34 dust scenario agree very well with TIRVIM observations, both in terms of thermal structure and tide characteristics.

**Bibliography:**

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