Characterization of a semidiurnal eastward-propagating tide at high northern latitudes with Mars Global Surveyor electron density profiles

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[1] Apparent phase velocities of zonal structure, estimated from Mars Global Surveyor (MGS) electron density profiles, are used to identify and characterize SE1, the semidiurnal eastward-propagating tide with zonal wave number one, at high northern latitudes during the summer of Mars Year 26. SE1 shows impressive phase stability with latitude, season, and local time. SE1 maintains a presence at amplitudes between 5 and 15% of the zonal mean at 125 ± 10 km altitude for most of the summer season. Further analyses using MGS electron density profiles will contribute to the identification and characterization of nonmigrating tides in the upper atmosphere of Mars.


1. Introduction

This paper reports new observations consistent with SE1, the semidiurnal eastward-propagating tide with zonal wave number one on Mars. We characterize its effect on ionospheric structure at high northern latitudes through analysis of electron density profiles obtained with MGS during northern summer of Mars Year 26 (MY26). (Clancy et al. [2000] defines Mars Year 1 as commencing on April 11, 1955.) The data in this work are from November 1, 2002–June 4, 2003, \( L_S = 89–200^\circ \), where \( L_S \) is the aerocentric longitude of the Sun and \( L_S = 0^\circ \) corresponds to vernal equinox in the northern hemisphere.

On Mars, the structure of the primary electron density peak is controlled by local photochemistry, and the altitude at which it forms depends on the path length of solar EUV radiation through the underlying neutral atmosphere [Bougher et al., 2001]. Mars lacks an appreciable internal magnetic field, and the influence of crustal magnetic fields is weak at the high northern latitudes considered in this work (60–85\(^\circ\)N) [Krymskii et al., 2003]. Thermal tides strongly affect the zonal structure of the neutral atmosphere at ionospheric altitudes, as observed by the accelerometer during MGS aerobraking [e.g., Forbes and Hagan, 2000; Forbes et al., 2002; Wilson, 2002; Withers et al., 2003]. The response of the ionosphere to tidal forcing is also apparent in radio occultation measurements of electron density from MGS [Bougher et al., 2001; Bougher et al., 2004; Cahoy et al., 2006]. The observed zonal variations of electron density arise primarily from the vertical displacement of the ionosphere that results from tidal modulation of neutral density.

2. Nonmigrating Tides

[5] Nonmigrating tides result from interaction between solar-locked migrating tides and planetary-scale forcing, such as that caused by topographic asymmetry [Zurek, 1976; Wilson and Hamilton, 1996; Forbes and Hagan, 2000; Forbes et al., 2002; Withers et al., 2003]. At a fixed latitude, \( \theta \), and height, \( z \), both migrating and nonmigrating tides can be represented as a variation in number density, \( n \), about the zonal mean of the form:

\[
n_{z,\lambda} = A_{z,\lambda} \cos(\sigma \Omega t + s \lambda - \psi_{z,\lambda})
\]

where \( A \) is amplitude, \( \psi \) is phase, \( \lambda \) is longitude, \( t \) is time in sols, \( \Omega = 2\pi \) sol\(^{-1}\) is the planetary rotation rate, \( \sigma \) is the temporal frequency of the wave (\( \sigma = 1 \) is diurnal, \( \sigma = 2 \) is semi diurnal), and \( s = 0, \pm 1, \pm 2, \pm 3 \ldots \) is the zonal wave number. For example, \( s = 1 \) is westward wave one, and \( s = 2 \) is eastward wave one. In this reference frame, the phase velocity is \( -\sigma \Omega / s \).

3. Tides at Fixed Local Time

used in this work, with sampling shown in detail in Figure 1 [Hinson et al., 1999; Bouger et al., 2001]. Over the entire
data set, latitude remains within a 25° band from 60°–85°N
(Figure 1, black line) with solar zenith angle (SZA) in the
range of 70°–85° (Figure 1, gray line). The sample spacing in
longitude is about 30°, with several gaps. The vertical
ordinate of the profiles is altitude above a reference areoid
with mean equatorial radius 3,396 km.

[7] We interpolate the data in season and longitude using
the method of Randell and Wu [2005], a Gaussian-weighted
average with standard deviations σ = 10° of longitude and
T = 4° of LS. We then subdivide the data, remove the zonal
mean, and perform zonal decomposition on separate slices of
4° LS, or roughly 7 sols. The local time and latitude of the
measurements within each slice are essentially constant.

[8] Local time increases monotonically across the data set. We
modify the equation representing tides at fixed latitude to the
local time reference frame using \( t = t_{LT} - \lambda/2\pi \):

\[
n_{s,x} = A_{s,x} \cos(\sigma \Omega_{LT} + (s - \sigma)\lambda - \psi_{s,x})
\]

The apparent phase velocity with respect to local time is:

\[
v_p = -\frac{\sigma \Omega}{s - \sigma}
\]

For fixed local time, the equation representing tides at fixed
latitude can be further simplified by setting
\( k = [s - \sigma] \) and
consolidating the now-constant \( \sigma \Omega_{LT} \) into a new phase
term, \( \lambda_k \):

\[
n_k = A_k \cos[k(\lambda - \lambda_k)]
\]

where

\[
\lambda_k = \psi_{s,x} - \sigma \Omega_{LT} (s - \sigma)
\]

It is also convenient to define \( \phi_k = k\lambda_k \), since the least-
squares wave decomposition used in this work solves for \( A_k \)
and \( \phi_k \). In observations at fixed local time, multiple
combinations of \( \sigma \) and \( s \) yield the same value of \( k \). For
time, \( \lambda_k \) would appear as \( k = [-1 - 2] = 3 \), as would any
other wave with \( |s - \sigma| = 3 \), such as the zonally symmetric
terdiurnal wave \((s = 3, s = 0)\).

4. Apparent Phase Velocity

[8] This MY26 data set comprises twenty-eight slices of
4° in LS at different fixed \( t_{LT} \). If \( \lambda_k \) remains fairly stable with
season, latitude, and SZA across several of the slices, we
use its progression in local time to estimate the apparent
phase velocity \( v_p \):

\[
\frac{d\lambda_k}{dt_{LT}} = \frac{1}{k} \frac{d\phi_k}{dt_{LT}} = -\frac{\sigma \Omega}{(s - \sigma)} = v_p
\]

If \( d\phi_k/dt_{LT} \) is determined to be positive, \((s - \sigma)\) must be
negative. Conversely, if \( d\phi_k/dt_{LT} \) is negative, \((s - \sigma)\) must be
positive. Each combination of \( \sigma \) and \( s \) yield a different
value for \( v_p \), as shown in Table 1 for \( k = 3 \). The estimate of
\( v_p \) can therefore be used, in principle, to determine the \( s \) and
\( \sigma \) of the dominant contributor.

5. Wave Decomposition Result

[8] We apply the same method of analysis used by Cahoy
et al. [2006], using weighted least squares to decompose the
zonial structure at fixed altitude. The sample spacing in
longitude is \( \sim 30° \), allowing consideration of zonal variation
for \( k = 1 - 6 \) without aliasing. Figure 2 (top) shows a sample
decomposition for \( k = 1 \)–6 for one \( 4° \) LS slice, from \( LS = 99°–103° \) at 125 km. The data exhibit well defined zonal
variation, and the spacing of the crests and troughs implies
the presence of structure with \( k > 4 \).

[10] Figures 2 (middle) and 2 (bottom) show the corresponding
individual amplitudes, \( A_k \), and phases, \( \phi_k \) over the entire
altitude range for this slice of data. The amplitudes for \( A_2 \)–\( A_5 \)
appear strongest for this subset of data. We note that the radio
occultation measurement senses the density of charged particles.
This should be kept in mind when viewing the resulting
amplitudes and phases, as the method is most sensitive at
125 km, just below the electron density peak, where electron
density, \( n_e \), and its gradient are strongest [Cahoy et al., 2006].

[11] Here, we focus primarily on \( k = 3 \). The phase for \( k = 3 \)
increases fairly linearly with altitude in the eastward
direction. There are some 5–10 km scale vertical regions
with variation, but overall, the vertical phase progression is
quite stable for this subset of data. These wave decompo-

| Table 1. Apparent Phase Velocities for \( k = 3 \) in deg. hr⁻¹ |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \lambda_k \) | \( \sigma = 1 \) | \( \sigma = 1 \) | \( \sigma = 2 \) | \( \sigma = 2 \) | \( \sigma = 3 \) | \( \sigma = 3 \) |
| \( s \) | 5 | -5 | 10 | -10 | 15 | -15 |
| \( v_p \) | 20 | -20 | 1 | 7 | 1 | 1.4 |
sition results for a single slice in the MY26 northern summer data set give a sense of the variety and level of detail embedded within the extensive catalog of radio occultation measurements performed by MGS.

6. Result for the Full MY26 Season

[12] We performed the same decomposition shown for a single slice in Figure 2 for twenty-seven additional $4^\circ L_S$ slices across the MY26 data set. The composite results for $k = 3$ are shown as $A_3$ and $\phi_3$ vs. $L_S$ in Figure 3.

[13] The $k = 3$ amplitude remains strong, from 5–15% of the zonal mean, at 125 ± 10 km for nearly the entire summer season. We further observe an increase in amplitude around 105 km, possibly associated with the lower secondary peak in electron density near that altitude. Early in the summer season and at earlier local time, there also appears to be notable strength in amplitude (up to 7.5%) at high altitudes (160 km). This could also be attributed to higher SZA, which results in a relatively small electron density. Another potential cause of variation is the slowly drifting latitude (Figure 1).

[14] The composite phase results for $k = 3$ for the entire MY26 summer season are shown in Figure 3 (middle) together with monotonically increasing local time (Figure 3, bottom) versus season. Considering that phase was solved for at each altitude independently, the stability of

Figure 2. (top) Example of wave structure at 125 km for a $4^\circ L_S$ subset of data, from $L_S = 99–103^\circ$ of MY26. The black circles are the measured values with ±1 standard deviation experimental error bars. The black line is the least-squares fit for $k = 1–6$. The gray lines are a 95% confidence envelope on the fit. Corresponding (middle) amplitudes ($A_{1–6}$) and (bottom) phases ($\phi_{1–6}$) shown from 105–160 km. Amplitude shown in units of $10^3$ cm$^{-3}$ and phase in degrees East longitude. Vertical dashed guidelines in amplitude map to 2.5, 5, and $7.5 \times 10^3$ cm$^{-3}$. Vertical dashed guidelines in phase correspond to $90^\circ$ spacing. Both shown with ±1 standard deviation gray envelopes. Phase data are shown with 2 km vertical spacing (dots) to clarify wraps in phase.

Figure 3. (top) Amplitude for $k = 3$ shown with season and altitude. Amplitude is shown as percent variation about the zonal mean. Contour intervals are 2.5%. (middle) Phase for $k = 3$ shown with season and altitude. The phase color map is circular, in 22.5$^\circ$ steps. Figure 2 for $\phi_3$ provides one absolute reference. (bottom) Local time vs. season.
weighted least-squares fit with the phase errors as weights. It is not necessarily representative of the stability for all local times than those discussed here. As for Figure 4, local time, making \( v_p = 3, \) errors in the initial phase calculation, a good candidate for apparent phase progression of phase for Forbes = 0). This result seems for observed \( k = 3 \) as shown in Figure 4 (bottom), using a weighted least-squares fit with the phase errors as weights. In Figure 5, we address both how the estimated \( v_p \) behaves with altitude, and whether or not the estimate yields a clear solution for \((\sigma, s)\) among the possibilities presented in Table 1. Each \( \times \) in Figure 5 represents an estimated apparent phase velocity, while the gray envelope marks \pm 1 standard deviation confidence in the goodness of the linear fit. The black vertical lines directly map to the possible apparent phase velocities shown in Table 1. For altitudes between 120–160 km, SE1 appears to be the closest candidate. At higher altitudes, where there is less confidence in the fit and stability, the estimated phase velocities drift toward non-migrating candidate DE2 (\( \sigma = 1, s = -2 \)) with \( v_p = 5^o \text{ hr}^{-1} \). At \( \sim 115 \) km, there is a single outlier on the zonally symmetric terdiurnal line (\( \sigma = 3, s = 0 \)). This result seems physically unlikely within such a narrow altitude range. Such outliers are likely due to a combination of weak amplitude at \( k = 3 \), errors in the initial phase calculation, contribution from other modes, or variation with season or latitude.

9. Conclusion

These results corroborate earlier studies that showed behavior consistent with semidiurnal frequency in MGS aerobraking and electron density data and that suggested SE1 as a strong candidate [Bougher et al., 2001; Withers et al., 2003]. Numerical simulations have also shown SE1 as a contributor to \( k = 3 \) structure observed in both MGS aerobraking neutral density and radio occultation electron density measurements during late spring in the Northern Hemisphere [cf. Wilson, 2002, Figure 3; Bougher et al., 2004, Figure 10; Angelats i Coll et al., 2004, Figure 5]. These simulations are all slightly earlier in \( L_S \) than the MY26 data presented here. Simulation results supporting SE1 were also reported at a later season (\( L_S = 270^o \)) [Forbes et al., 2002, Figure 6]. Our results extend this work by providing direct experimental characterization of SE1 at high northern latitudes for the full summer season of MY26. SE1 shows impressive phase stability with altitude, season and local time, as well as maintaining a presence at amplitudes between 5 and 15% of the electron density zonal mean at 125 \pm 10 km altitude. Further analyses using MGS electron density profiles will contribute to the iden-

7. Phase Stability

\[ \phi_3 \] with both altitude and season is remarkable, particularly in the morning (earlier \( L_S \)). The phase change with season appears, at most altitudes, to be controlled by the change in local time, making \( \phi_3 \) a good candidate for apparent phase velocity estimation.

8. Phase Velocity Result

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Figure 4. (top) \( \lambda_3 \) at 125 km (circles) versus \( L_S \). Error bars represent \pm 1 standard deviation. (bottom) \( \lambda_3 \) as for Figure 4 (top), but shown versus local time. The slope of the black line through the solid gray circles is the estimated \( v_p \). For this example at 125 km, \( v_p = 11^o \text{ hr}^{-1} \).

Figure 5. Estimated apparent phase velocities for \( k = 3 \) vs. altitude. Vertical black lines compare the estimates with predictions in Table 1.
tification and characterization of nonmigrating tides in the upper atmosphere of Mars.

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References


