THE ATMOSPHERE OF MARS: OBSERVATIONS OF THERMAL TIDES AT, ABOVE, AND AROUND GALE CRATER FROM THE SURFACE AND FROM ORBIT

1. Motivation and objectives

Thermal tides are global-scale oscillations in atmospheric properties (density, pressure, temperature, winds) whose periods are integer fractions of the martian day, or sol (Chapman and Lindzen, 1970). They are an important aspect of the dynamics of the atmosphere of Mars (Zurek, 1976, 1986; Leovy and Zurek, 1979; Leovy, 1981; Zurek and Leovy, 1981; Tillman, 1988; Wilson and Hamilton, 1996; Bridger and Murphy, 1998; Keating et al., 1998; Banfield et al., 2000, 2003; Wilson, 2002; Forbes et al., 2002, 2004; Withers et al., 2003, 2011; Forbes, 2004; Moudden and Forbes, 2008, 2010, 2011, 2014; Lee et al., 2009; Sato et al., 2011; Guzewich et al., 2012, 2014; Kleinbohl et al., 2013). At Mars, they are a particularly significant aspect of the climate system due to the low thermal inertia of the atmosphere, which causes strong day-night temperature variations (Zurek et al., 1992). These variations become thermal tides. Two of most familiar effects of thermal tides are regular daily variations in surface pressure with local solar time (Fig. 1) and oscillations with altitude in vertical temperature profiles (Fig. 2).

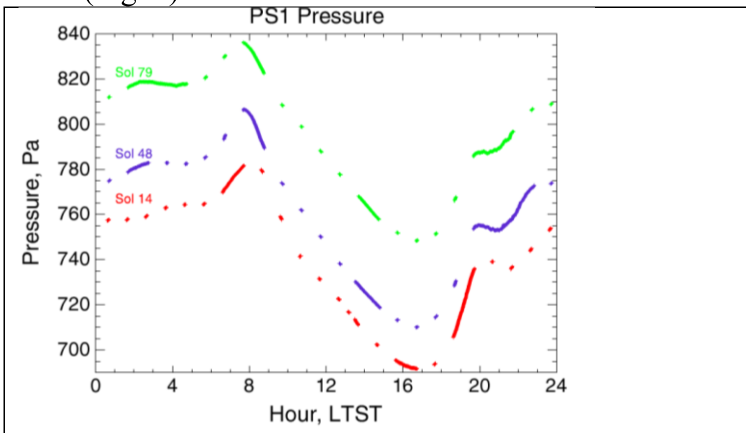

Fig. 1 (top) Dependence of surface pressure measured by Curiosity's pressure sensor 1 (PS1) during sols 14 (red), 48 (green), and 79 (blue) on local true solar time (LTST). Fig. 4 of Haberle et al. (2014).

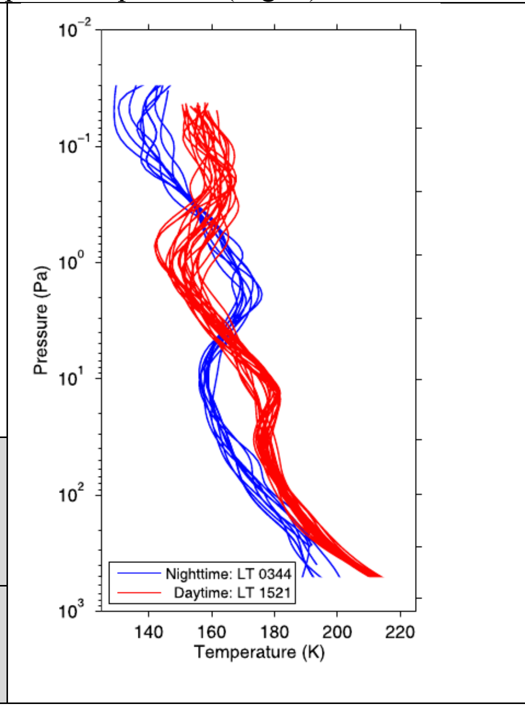

Fig. 2 (right) Daytime (red) and nighttime (blue) temperature-pressure profiles from MCS at 45°N-50°N and Ls=156° to 162°. Fig. 1 of Lee et al. (2009).

In the Viking era, when capable meteorological stations operated on two long-duration landers, thermal tides were primarily studied via their effects on time series of surface pressure at the two Viking landing sites (e.g., Wilson and Hamilton, 1996). Due to the limited capabilities of the Viking orbital instruments for studying atmospheric conditions, global-scale effects were less well-studied in this era.

During the decade-and-a-half from the arrival of Mars Global Surveyor (MGS) to the landing of Curiosity, when the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) and Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) instruments provided abundant temperature-pressure profiles across the globe at two local solar times, thermal tides were primarily studied via their effects on the global-scale distribution of atmospheric temperatures (e.g., Banfield et al., 2000, 2003; Lee et al., 2009; Guzewich et al., 2012). Surface pressure variations were not studied due to a lack of landed data. Lamentably, the long-lived

Spirit and Opportunity rovers were not equipped with any meteorological sensors. Although Pathfinder and Phoenix did operate meteorological sensors (Schofield et al., 1997; Haberle et al., 1999; Taylor et al., 2008, 2010; Tamppari et al., 2010), the short durations of their missions and, for Phoenix, its polar location meant that their impact on studies of thermal tides was limited.

This situation changed dramatically with the safe landing of Curiosity and the continued operation of MCS. For the first time ever, we have the opportunity to simultaneously investigate the effects of thermal tides at a surface location, above that surface location, and in the global atmosphere. Doing so will provide a much richer view of this important atmospheric process than did Viking-era analyses, which were limited to two surface locations, or MGS-era analyses, which were limited to two local solar times. The availability of this unprecedented combination of datasets means that we are finally able to answer these important questions:

- How do the effects of thermal tides, whose effects decrease with increasing latitude, at Curiosity's equatorial landing site differ from those at the mid-latitude Viking landing sites?
- How are the effects of thermal tides on surface pressure measurements related to their effects on the atmospheric temperature structure directly overhead?
- Do general circulation models accurately predict both the landed and orbital views of thermal tides?

These questions are important in the context of Mars science. Answering them will:

- Improve understanding of one of the most important processes in the climate of Mars
- Encourage the development of an integrated "whole atmosphere" view of the martian climate system by strengthening links between surface meteorology and orbital meteorology

Table 1. Objectives	
1. To use Curiosity pressure data from Gale crater to characterize the effects of thermal tides at the surface	**Task A**
2. To use simultaneous Curiosity pressure data and MCS temperature-pressure profiles above Gale crater to connect the effects of thermal tides at the surface and above the surface	**Task B**
3. To use MCS temperature-pressure profiles from around the planet to place the behavior of thermal tides at and above Gale crater into a global context	**Task C**

The three objectives of this proposal (Table 1) are designed to produce a comprehensive understanding of thermal tides in the atmosphere of Mars that unifies landed and orbital measurements. First, we shall analyze characteristics of thermal tides in the Curiosity pressure data, as was done for Viking (**Task A**). Next, we shall connect this landed view (one location, all local times) and the orbital view (all locations, few local times). This will eliminate degeneracies that affect studies of thermal tides that are based on only one of these views. We shall do this by measuring the amplitudes and phases of several classes of thermal tides in the equatorial atmosphere above Gale crater using MCS data, then relating these results to conditions at Curiosity (**Task B**). Finally, we shall test whether the set of thermal tides that we determine to be present from these equatorial observations is consistent with the thermal structure of the atmosphere at other latitudes (**Task C**). We introduce thermal tides in Sections 2 and 3, discuss the Curiosity and MCS data in Sections 4 and 5, and outline **Tasks A-C** in Sections 6-8.

2. Introduction to thermal tides in the atmosphere of Mars

Since Mars has a fluid atmosphere, solid surface, and Earth-like size, rotational period, and obliquity, the behavior of its atmosphere is similar in many ways to that of Earth's (Zurek et al., 1992; Leovy, 2001). The main difference is the lack of oceans and dense clouds of liquid water, which act to moderate Earth's climatic extremes, and the increased orbital eccentricity. Thus, diurnal and seasonal variations in weather are larger on desert-like Mars than on Earth. In the absence of abundant water, dust plays the major role in controlling the thermal structure of the atmosphere, which in turn determines the global-scale circulation of the atmosphere.

The regular diurnal variation in solar heating, which ultimately drives all atmospheric processes, causes global-scale oscillations in atmospheric properties (density, pressure, temperature, winds). Since solar heating is periodic with a period of one martian day, or sol, the atmospheric oscillations that it produces must have periods that are integer fractions of a sol. Oscillations can be diurnal (one period per sol), semi-diurnal (two periods per sol), ter-diurnal (three periods per sol), quad-diurnal (four periods per sol), and so on. Similarly, the atmospheric oscillations must also have an integer number of cycles per 360^{o} of longitude. The energy per unit volume associated with these atmospheric oscillations is proportional to the product of the atmospheric density and the square of the oscillation's amplitude (Chapman and Lindzen, 1970). In the idealized dissipation-free case, conservation of energy requires that the amplitude of an oscillation in temperature or other property increase with altitude to compensate for the decreasing atmospheric density.

These global-scale oscillations are called thermal tides by analogy to gravitational tides in Earth's oceans. They are a more significant part of the atmosphere on Mars than on Earth due to the low thermal inertia of Mars's atmosphere, which causes strong day-night temperature variations (Zurek et al., 1992). Also, the lack of an ozone layer and associated temperature maximum (stratopause) encourages their propagation to high altitudes, where amplitudes become large and the effects of these atmospheric oscillations become very substantial.

The governing equations permit a range of possible tidal oscillations, each with a specific temporal, zonal, meridional, and vertical structure (Chapman and Lindzen, 1970). Temporal variations in solar forcing are not purely diurnal: semi-diurnal and higher order contributions exist because the solar forcing is zero, not negative, at night. Diurnal and semi-diurnal tides are typically the strongest, but their relative importance varies. Since solar heating tracks the Sun across the sky, the strongest tidal modes are those that move westward at a rate of 360^{0} of longitude per sol. Such modes, which are called "migrating" tides, are strong in the lower and middle atmosphere. Modes that advance in longitude at a different, non-Sun-tracking, rate, which are called "non-migrating" tides, are most important in the upper atmosphere, but they can also play a role at lower altitudes.

The amplitude A of a tidal oscillation in the atmosphere is a function of altitude, z, latitude, θ, longitude, ϕ, and universal time, t_{UT}. A tidal oscillation with a specific period and zonal structure can be represented as in Eqn. 1, where n is a non-negative integer, s is an integer, Ω is the planetary rotation rate of 2π sol^{-1}, and ψ is a phase. Diurnal tides have n=1, semi-diurnal tides have n=2, etc. In a fixed UT frame, a tide with $|s|$=1 has one cycle per 360^{o} of longitude (wave-

1), a tide with $|s|=2$ has two cycles per 360° of longitude (wave-2), etc. Migrating tides have $n=s$ and non-migrating tides have $n \neq s$. As local solar time, t_{LST}, satisfies $\Omega t_{UT} = \Omega t_{LST} - \phi$, Eqn. 1 is equivalent to Eqn. 2. In a fixed LST frame, a tide with $|n-s|=1$ has one cycle per 360° of longitude (wave-1), etc. Thus any zonal structure seen at fixed local solar time can be attributed to a non-migrating tide with $n \neq s$. For instance, diurnal Kelvin wave 1 (DK1), which is often one of the strongest non-migrating tidal modes, has $n=1$, $s=-1$, and $|n-s|=2$, and so it has 2 cycles per 360° of longitude (wave-2) in a fixed LST reference frame.

$$A = A_{n,s}(z,\theta)\cos\left(n\Omega t_{UT} + s\phi - \psi_{n,s}\right) \qquad \text{(Eqn 1)}$$

$$A = A_{n,s}(z,\theta)\cos\left(n\Omega t_{LST} + (s-n)\phi - \psi_{n,s}\right) \qquad \text{(Eqn 2)}$$

When studying atmospheric properties and processes, it is often desirable to determine values of n and s, the vertical structure, and the meridional structure of the thermal tide that is responsible for an observed oscillation (Fig. 3). Given complete observations at all altitudes, latitudes, longitudes, and local solar times, that is trivial. Of course, such complete observations are not available and identifying the tidal oscillation responsible requires detective work that takes advantage of the properties of tides.

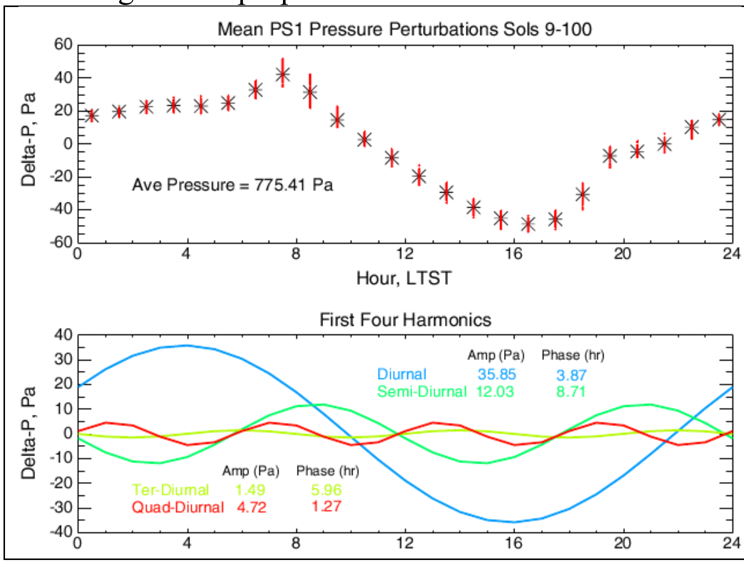

Fig. 3. (top) Pressure departure from daily mean for first 100 sols of Curiosity's mission (Ls~180°) as a function of local solar time. Red dots are actual values and black asterisks are the corresponding means. (bottom) Harmonic fit to data in top panel. Blue curve is diurnal, green semi-diurnal, light green ter-diurnal, and red quad-diurnal. Here the diurnal amplitude is 3x the semi-diurnal amplitude, which is 3x the quad-diurnal amplitude, which is 3x the ter-diurnal amplitude. Both panels from Fig. 2 of Haberle et al. (2014).

In principle, an infinite series of basis functions (Hough modes found from classical tidal theory, Chapman and Lindzen, 1970) contribute to the dependence of A on altitude and latitude for a given n,s tidal mode. In practice, however, a single basis function is the dominant contribution to a given n,s tidal oscillation. Hence a given n,s tidal oscillation has more-or-less the same meridional structure and vertical wavelength as its most dominant basis function, which we call a tidal mode. The dominant basis function is typically the one whose variation with latitude is least. This basis function will have a broad peak centered on the equator. This disturbance can be "efficiently excited" by solar heating, since the greater intensity of solar heating in the tropics than at the poles favors tidal modes with compatible meridional structures.

The dominant basis function will also have a unique vertical wavelength. If it is real, that tidal mode is a vertically propagating wave. If it is imaginary, that tidal mode is an evanescent vertical wave. The migrating semi-diurnal tide has a much longer vertical wavelength (~200 km) than the migrating diurnal tide (~30 km) (Section 3.2). Thus, when the atmosphere is very dusty and solar heating is vertically extended, the migrating semi-diurnal tide is more "efficiently excited" by solar heating than usual and its amplitude is enhanced (Fig. 4). Normally, the absorption of solar heating near and at the surface favors modes that have a relatively short vertical wavelength.

Taken to its literal extreme, the concept of dominance of each *n,s* tidal oscillation by one basis function (tidal mode) and neglect of non-migrating tides ($n \neq s$) implies that all diurnal tidal variations can be attributed to one basis function (tidal mode), which has a well-defined meridional and vertical structure. All semi-diurnal tidal variations can be similarly condensed. This provides a useful framework for initial interpretation of observations, although, in practice, matters are more complicated than this simplified reasoning suggests.

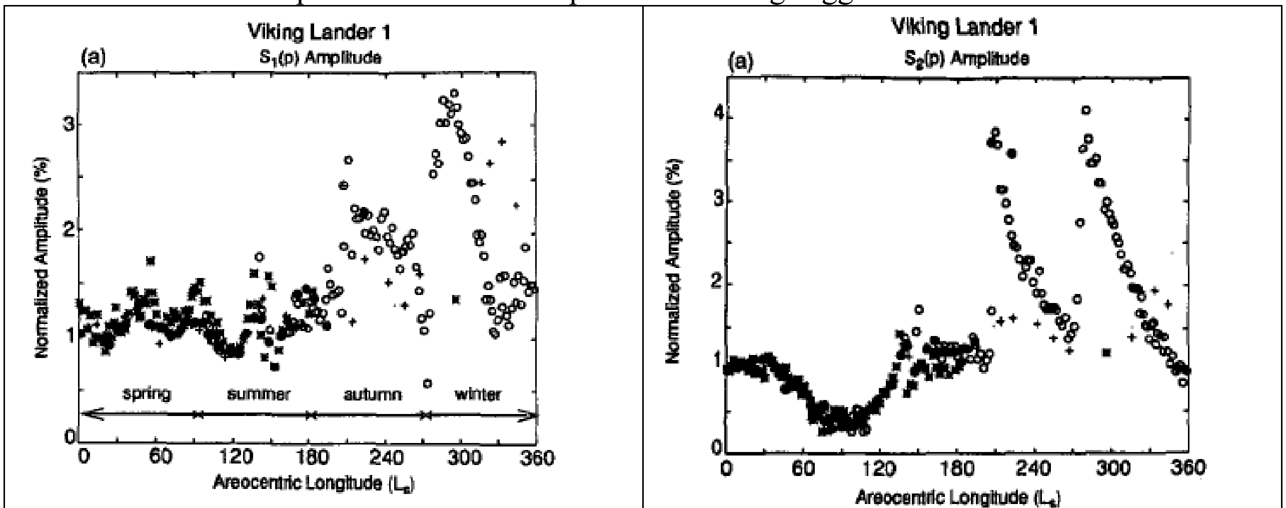

Fig. 4. Amplitude of diurnal (left) and semi-diurnal (right) variations in surface pressure at Viking 1 as a function of Ls. Symbols are: open circles, year 1; stars, year 2; crosses, year 3; filled circles, year 4. Amplitudes are typically 1% of the mean, but increase abruptly to 4% during global dust storms. The corresponding phase plots (not shown) also show distinctive changes with season. Adapted from Figs. 1-2 of Wilson and Hamilton (1996).

A more powerful approach for identifying tidal modes is to leverage complementary observations. When observations at a fixed location (e.g., Curiosity) show a dependence on local time, many different *n,s* tidal modes may, in principle, contribute. Such observations constrain only *n*. By contrast, when observations at a fixed local solar time (e.g., MCS) show a dependence on longitude, a different set of *n,s* tidal modes may, in principle, contribute. Such observations constrain $|n\text{-}s|$. However, only a few *n,s* tidal modes will be consistent with both sets of data.

3. Three important effects of thermal tides

3.1. Diurnal variations in surface pressure

The surface pressure observed at a landing site on Mars on a given sol varies with local solar time. These variations are periodic and highly repeatable from one sol to the next (Figs. 1 and 3). A harmonic decomposition of these variations yields the amplitudes and phases of the most significant temporal variations (Fig. 3). These amplitudes and phases are sensitive to the local and larger-scale dust distribution (Zurek and Leovy, 1981; Tillman, 1988; Haberle et al., 2014). A migrating tidal mode is probably the major contributor to each harmonic component, but non-migrating tidal modes may also contribute significantly. Tidal variations in Curiosity's surface pressure data (described in Section 4) will be the focus of **Task A** (described in Section 6).

Haberle et al. (2014) saw striking changes in the amplitude and phase of the diurnal component of Curiosity's pressure variations at Ls=200^{o}. They suggested that these changes could be associated with seasonal changes in DK1, a non-migrating tidal mode introduced in Section 2. The presence of DK1 has been seen in many orbital datasets, particularly in the tropics, so it is highly plausible that it could affect diurnal variations in surface pressure. However, since Haberle et al. (2014) used only Curiosity data, they were not able to establish whether DK1 was present in the atmosphere or, if present, how significant it was relative to the migrating diurnal tide. As we introduce other observable consequences of thermal tides in Sections 3.2 and 3.3, we shall outline a method for answering these questions.

3.2. Variations in atmospheric temperature with altitude

Tides introduce a pattern of alternating temperature maxima and minima into a vertical temperature profile (Fig. 2). The altitude separation of successive maxima indicates the vertical wavelength of the dominant tidal mode and the difference between maximum and minimum temperatures indicates its amplitude. A single vertical profile is of limited value, however, since it can be difficult to discern temperature extrema relative to a background trend of temperatures decreasing with increasing altitude. Also, a profile at a single local time cannot unambiguously determine whether the dominant tidal mode is diurnal, semi-diurnal, or higher order.

Conveniently, MCS temperature-pressure profiles are acquired at two local solar times separated by half a sol (Fig. 2). The effects of any diurnal (and ter-diurnal) variations are exactly in anti-phase between day and night at all altitudes. Daytime temperature maxima occur at the same pressure level as nighttime temperature minima, and vice versa. Conversely, the effects of any semi-diurnal (or quad-diurnal) variation are exactly in phase at all altitudes. Thus a profile of the difference between daytime and nighttime temperatures shows the effects of diurnal tidal modes clearly, but masks all effects of semi-diurnal and quad-diurnal tidal modes. The vertical wavelength and temperature amplitude of the dominant diurnal tidal mode can hence be readily found from the difference profile. The altitudes where the temperature difference is maximized (e.g., 2 Pa in Fig. 2) are also of interest, as they indicate the phase of the tide at that local time.

Following the reasoning outlined at the end of Section 2, each tidal mode can be expected to have a specific vertical wavelength, λ. This wavelength is related to the thermal structure of the atmosphere and the properties of the tidal mode (Chapman and Lindzen, 1970). Assuming a nominal temperature of 180 K, scale height of 9 km, and static stability of 5 K km^{-1} (Magalhaes et al., 1999), the vertical wavelengths of the diurnal, semi-diurnal, ter-diurnal, and quad-diurnal migrating tidal modes are 30 km, ~200 km, ~200 km (evanescent), and ~200 km (evanescent), respectively. The vertical wavelength of DK1 is ~200 km (evanescent) (Withers et al., 2003). These wavelengths enable us to further constrain the tidal mode responsible for the temperature variations in Fig. 2 whose period is diurnal. The altitude spacing of these variations is consistent with the 30 km wavelength predicted for the migrating diurnal tidal mode, but is much too small for DK1. Had Haberle et al. (2014) seen this altitude spacing in temperature profiles above Gale crater, it would have shown that that the migrating diurnal tide is significantly stronger than DK1. Note that even when DK1 and other non-migrating tides are not strong enough to be visible in zonal mean representations like Fig. 2, their amplitudes and phases can be found from analysis of zonal variations in MCS temperature differences (Eqn. 2, Section 3.4, and Guzewich et al., 2012). Tidal variations in MCS atmospheric temperature measurements (described in Section 5) above Gale crater will be the focus of **Task B** (described in Section 7).

Since pressure is merely the weight of the overlying atmospheric column, the amplitude of these variations in atmospheric temperature is related to the amplitude of variations in surface pressure. Similarly, the pressure levels at which daytime temperature maxima occur are related to the phase of variations in surface pressure. This links **Tasks A and B**.

3.3. Variations in tidal properties with latitude

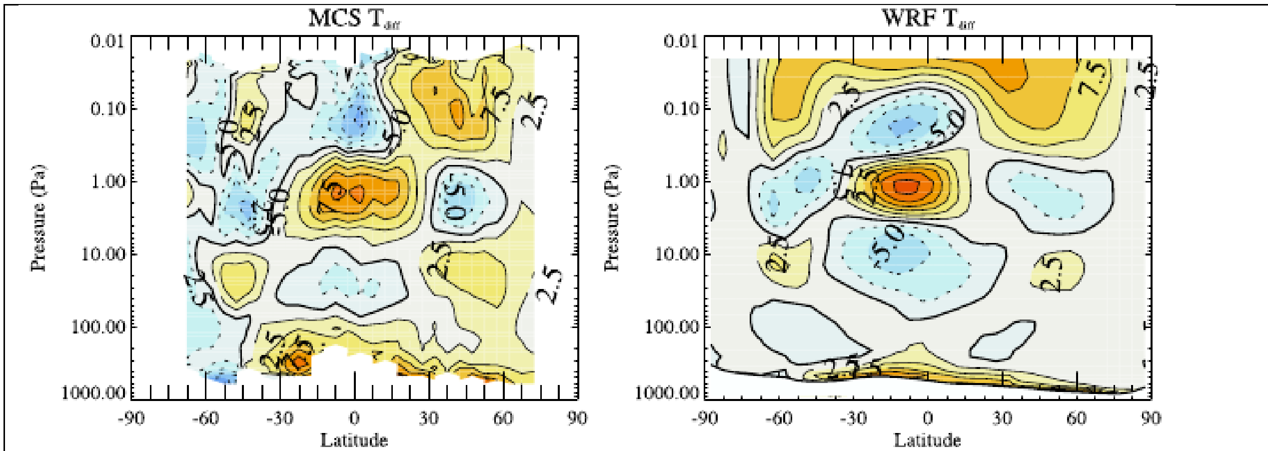

Fig. 5. (left) Zonal mean T_{diff} (Kelvin) from MCS observations at $Ls=135^o$ to 165^o. $2T_{diff}$ is the difference between daytime and nighttime temperatures. Contour interval is 2.5 K. This is the same season as Fig. 2 and temperature differences in Fig. 2 can be matched to features at 50^oN in this panel. (right) A numerical simulation by the Mars WRF model of the observed temperature difference. Both panels from Fig. 11 of Lee et al. (2009).

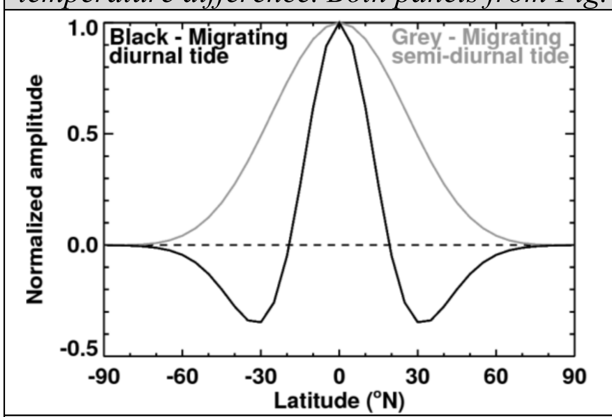

Fig. 6. Meridional structures of the idealized migrating diurnal (black) and semi-diurnal (grey) tidal modes. The ter-diurnal and quad-diurnal modes are similar to the semi-diurnal mode, as is DK1.

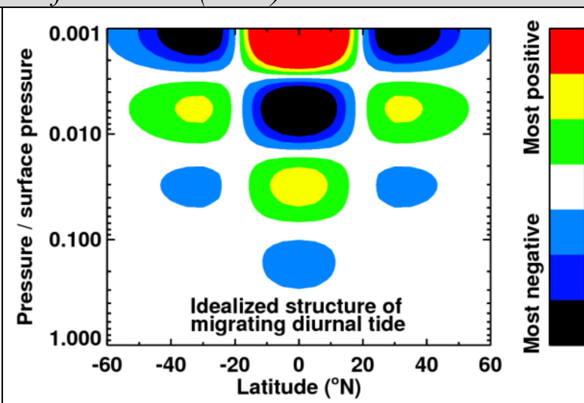

Fig. 7. Idealized structure of the migrating diurnal tide, produced by specifying meridional structure, vertical wavelength, and amplification with increasing altitude. From most negative to most positive, the color sequence is black, dark blue, light blue, white (zero), green, yellow, red.

Since tidal modes have meridional structure, patterns in the difference between daytime and nighttime MCS temperatures vary with latitude. This is illustrated in Fig. 5, where the difference between daytime and nighttime temperatures has a maximum (daytime much warmer than nighttime) at 2 Pa in the tropics, but a minimum (daytime much colder than nighttime) at the same pressure level at mid-latitudes. Trends at other pressure levels reverse similarly at 30^o latitude. This is consistent with the meridional structure of the migrating diurnal tide in classical tidal theory (Fig. 6), but inconsistent with the meridional structure of DK1 (Fig. 6). Numerical models and classical tidal theory can predict such patterns of positive and negative temperature extrema, as shown in Figs. 5 and 7. Fig. 5 shows that peak tidal amplitudes occur at the equator. This is consistent with the landed surface pressure data in Figs. 3 and 4, where the diurnal tidal amplitude at Ls~180^o is ~4% for equatorial Curiosity, but only ~1% for mid-latitude Viking 1. Tidal variations in MCS atmospheric temperature measurements (described in Section 5) with latitude will be the focus of **Task C** (described in Section 8).

3.4. Synthesis of different tidal effects

As emphasized at the end of Section 2, the unprecedented partnership of Curiosity and MCS data permits us to untangle overlapping tidal modes. We illustrated this in the preceding discussion using the example of a diurnal variation in a surface pressure record (Figs. 1, 3, and 4, and Section 3.1). Many tidal modes, including the migrating diurnal tide and the non-migrating DK1 tidal mode, could be responsible for such variations, but the relative importances of these possible contributors cannot be determined from landed data alone. Analysis of the vertical structure of the temperature profile above the location of the surface pressure sensor and zonal variations in temperature at that latitude can discriminate between possible tidal modes (Figs. 2 and 8, and Section 3.2). Fig. 8 confirms that DK1 and other non-migrating tides can be identified in MCS data. Analysis of meridional variations in the atmosphere's thermal structure can further discriminate between possible tidal modes (Figs. 5, 6, and 7, and Section 3.3). These three stages are each the focus of one of our proposed **Tasks** (Sections 6-8). Before describing **Tasks A-C** in detail, we first demonstrate that the available data are sufficient for studying thermal tides.

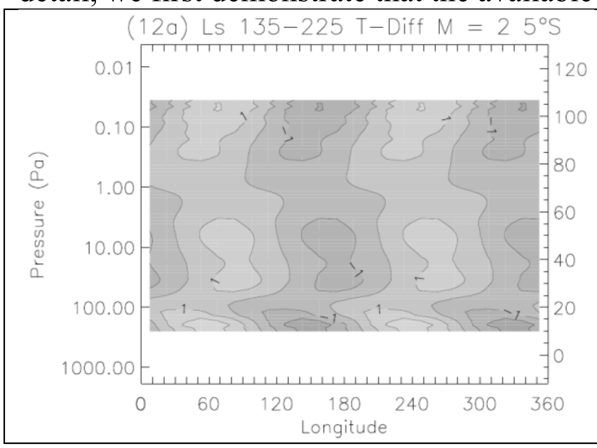

Fig. 8. The amplitude and phase of the wave-2 zonal component (2 cycles per 360^o of longitude) of MCS T_{diff} at Ls=135^o-225^o and 5^{o}S latitude. As noted in Section 2, DK1 dominates this wave-2 zonal component. Maxima and minima stay fixed in longitude as altitude increases, a characteristic of DK1. From Fig. 12 of Guzewich et al. (2012).

4. Curiosity surface pressure measurements

At the present time, the PDS contains Curiosity data from 15 August 2012 to 28 March 2014 (mission sol 9, Ls=155^o, MY 31, to mission sol 583, Ls=108^o, MY 32). Millions of individual pressure measurements are available. At a minimum, Curiosity acquires pressure measurements for the first 5 minutes of every hour. When resources permit, additional data are collected in one hour blocks. The data volume varies between 2 hours and 9 hours per sol. Curiosity carries four pressure sensors, two of which are currently reserved for calibration. Of the two operational pressure sensors, one (PS1) is optimized for high stability, but at the cost of contaminated readings during the first few minutes of an observing session due to a slow warm-up, and the other (PS2) is optimized for fast warm-up, but at the cost of reduced stability. During an observing session, PS1 is sampled every 16 seconds and PS2 is sampled every second. The performance of the pressure sensors is discussed at length by Harri et al. (2014). Within the confines of this proposal, this discussion can be summarized as the uncertainty in an individual pressure measurement being ~2 Pa. Our proposed analyses of Curiosity pressure data will focus on pressure variations on a timescale of hours, and we shall follow the best practices recommended by Harri et al. (2014) and Haberle et al. (2014) for such studies.

Fig. 9 shows how the daily pressure cycle has evolved during the mission. It shows the average pressure reading for every hour of every sol, expressed as the deviation from the daily average. Hence a value of 0.10 means the pressure at that local solar time and sol is 10% greater than the daily average for that sol. The archived pressures are accompanied by the UTC time, local mean solar time, and mission sol. We shall use SPICE to convert time into local true solar time and Ls, both of which are most appropriate for atmospheric studies. Fig. 9 also illustrates the excellent data coverage. Fig. 10 shows an example of the daily pressure cycle from Ls=60^o. The timing of the largest maxima and minima is consistent with Figs. 1 and 3. The amplitudes and phases of the main components of the diurnal variation are noted as well (like Fig. 3). We will also track the goodness of fit and the uncertainties in fitted amplitudes and phases in our proposed work.

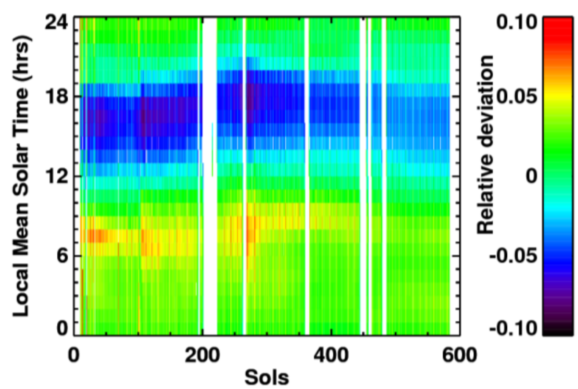

Fig. 9. Deviation of pressure from the daily average over the course of Curiosity's mission. Tides became weaker over the course of the mission (reds and dark blues present at earliest sols are not present at latest sols.)

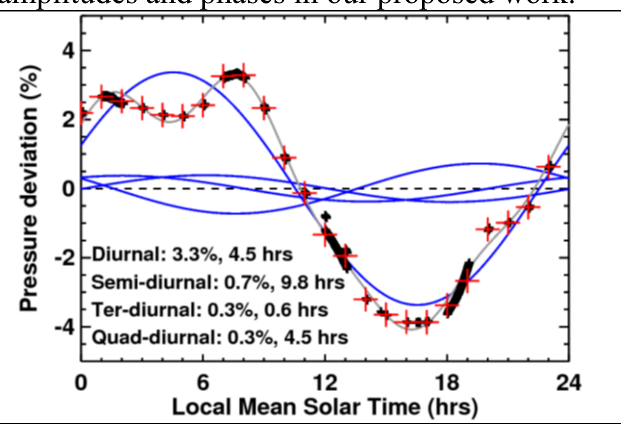

Fig. 10. Daily pressure cycle at Ls=60^o (data from 10 and 17 December 2013). Black crosses mark data points, large red crosses show hourly average pressure, the grey line is a harmonic fit to the red crosses, and the four blue lines are the four harmonic components.

5. MCS temperature-pressure profiles

MCS, a limb sounding infrared radiometer, has operated since 2006. Its most useful data are profiles of temperature as a function of pressure. Vertical resolution is ~5 km, ample to resolve long-wavelength tidal variations, and horizontal resolution is ~200 km. From 5 to 300 Pa, temperature uncertainties are ~0.4 K. At higher pressures, where the atmosphere is more opaque, errors are larger, ~0.5-3 K. At lower pressures, where the atmosphere is tenuous, errors are also larger, increasing to 10 K near 0.06 Pa (~80 km). These temperature uncertainties are reduced if several individual profiles are averaged together. Fig. 11 shows daytime and nighttime MCS profiles from above Curiosity's landing site at the time Curiosity collected Figure 10's data.

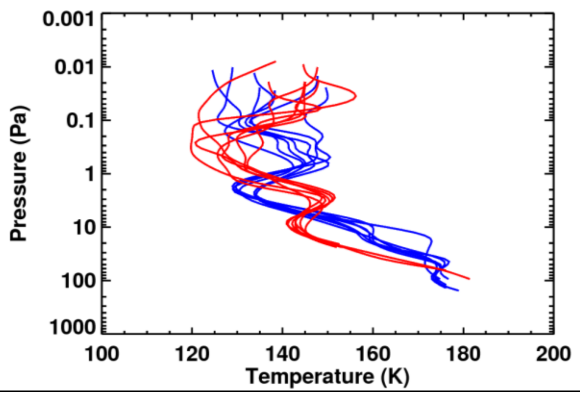

Fig. 11. MCS temperature profiles above Gale crater at Ls=60^o (10-13 December 2013). The profiles were acquired at the same dates as the Curiosity pressure data shown in Fig. 10. Daytime profiles are in red and nighttime profiles are in blue. Temperature variations consistent with the migrating diurnal tide are present.

MCS is not restricted solely to "in track" measurements that primarily sample 3am and 3pm local times. Since 2010, about half its observations have been acquired in "off track" campaigns that, in the tropics, sample six local times. This additional coverage in local time was sufficient for Kleinbohl et al. (2013) to characterize how the amplitude and phase of the migrating semi-diurnal tide, which is undetectable in 3am/3pm data, vary with altitude and latitude. They found that the migrating diurnal and semi-diurnal tidal modes have comparable magnitudes, and that the semi-diurnal tidal mode is persistent throughout the year with a broad meridional structure and long vertical wavelength consistent with classical tidal theory (Sections 3.2 and 3.3).

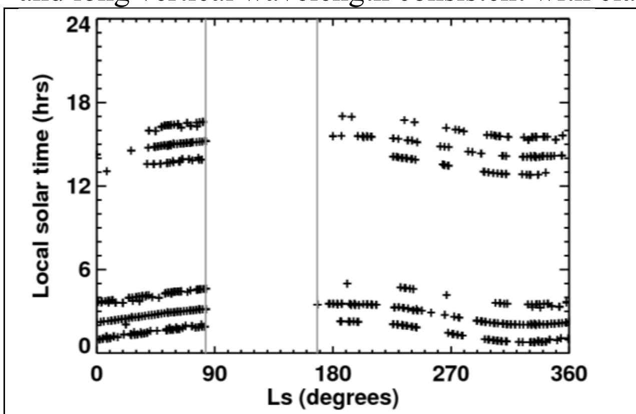

Fig. 12. Local solar time as a function of Ls for the 856 MCS profiles acquired since Curiosity's landing within 5^o latitude and longitude of the landing site. Grey lines mark the start of the data series at Ls=168^o of MY 31 and the end at Ls=83^o of MY 32.

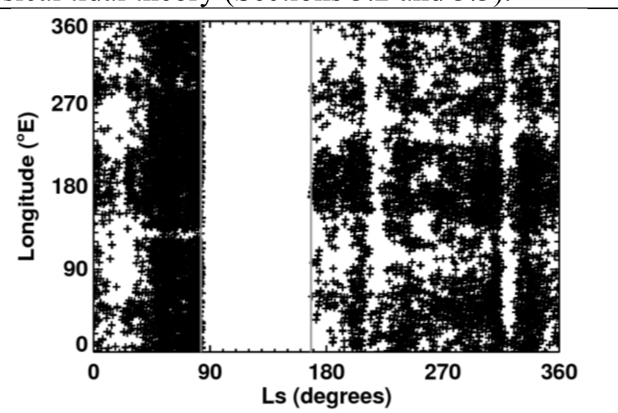

Fig. 13. Longitude as a function of Ls for the 14,447 MCS profiles acquired at daytime local solar times within 5^o latitude of Curiosity's landing site. Grey lines lines mark the start of the data series at Ls=168^o of MY 31 and the end at Ls=83^o of MY 32.

More than 10^5 MCS profiles acquired since Curiosity landed are available from the PDS. These span from 8 September 2014 (Ls=168^o, MY 31) to 31 January 2014 (Ls=83^o, MY 32). These data do not cover the first month of Curiosity's mission due to a hiatus in which MRO was devoted to supporting Curiosity. Data coverage is sufficient for the proposed work (Figs. 12-13). Fig. 12 shows that many MCS profiles are available above Gale crater throughout the Mars year. The most significant gap is the near-absence of daytime profiles at Ls=0^o-30^o, which is only one "month" of the Mars year. The rest of the year will be filled in with the next release of MCS profiles. Fig. 13 shows that the MCS profiles have adequate zonal coverage at most seasons.

The MCS team's "version 2" processing algorithm is responsible for the small gaps in coverage that do exist. This version is unable to retrieve profiles when the aerosol opacity is high, which is common at the equator during the aphelion cloud belt season. Figs. 12-13 show that this problem is not catastrophic for our proposed work. At seasons where gaps exist, data will exist at mid-latitudes. Since thermal tides are global-scale oscillations in atmospheric properties, the dominant tidal modes can be identified from meridional, vertical, and zonal patterns even with gaps at equatorial latitudes (Section 3.3). If the consequences of a particular data gap are severe, then they can be mitigated by examining profiles from the same season and location in other years. In any case, the MCS team has developed and validated an improved algorithm and plans to release a comprehensive "version 3" set of profiles to the PDS soon.

6. Task A: Effects of thermal tides on the surface pressure in Gale crater

To prepare for this **Task**, we shall determine the amplitudes and phases of the diurnal to quad-diurnal harmonic components of Curiosity's surface pressure data (Figs. 3 and 10). The goodness of fit and uncertainties in the fitted amplitudes and phases will also be found. (These data products may be useful to other researchers, and so we shall make them available as supplemental information to our published papers.) Changes in the fitted amplitudes and phases from sol to sol will indicate changes in the surrounding atmosphere.

First, we shall conduct a broad survey of the results. We shall compare the observed tidal amplitudes and phases to predictions by the Mars Climate Database (Lewis et al., 1999) in order to see how well the observed behavior fits within the context of present understanding of the atmosphere. Significant differences between observations and model will highlight issues of potential importance. Viking-era studies suggested a strong correlation between the amplitude of the semi-diurnal tide and the atmospheric dust loading (e.g., Zurek and Leovy, 1981), but that was not seen in the first analysis of Curiosity data (Haberle et al., 2014). To explore this issue, which illuminates how the atmospheric dust distribution affects the strength of tidal modes, we shall compare observed tidal amplitudes to dust content on local (Curiosity), regional (THEMIS/MCS), and global (THEMIS/MCS) scales. Since different tidal modes have different meridional and vertical structures, they will respond differently to dust events with different spatial extents. We have used dust data in earlier projects (Withers and Smith, 2006; Withers and Pratt, 2013).

Second, we shall focus on changes in the tidal properties with time over a range of timescales. We shall search for instances of short-lived changes in tidal amplitudes and phases. Such changes would indicate the passage of a moderately small-scale atmospheric event, such as a localized dust event, that briefly perturbs the structure of thermal tides in the vicinity of Gale crater. Where such changes are found, we shall inspect other atmospheric datasets (e.g., Curiosity atmospheric opacity data, MARCI images, MCS profiles) in order to better characterize this event. We shall also identify longer-lived changes in tidal amplitudes and phases, distinguishing between changes with abrupt onsets most likely caused by large-scale dust events and gradual changes most likely caused by seasonal cycles in the atmosphere. Note that even gradual changes could be caused by evolution in the atmospheric dust loading, albeit on a slower timescale than dust storm onset. For the abrupt changes that are most likely caused by large-scale dust storms, we shall inspect other atmospheric datasets (e.g., Curiosity atmospheric opacity data, MARCI images, MCS profiles) in order to determine how changes in dust loading, thermal structure, and pressure variations are connected. For instance, do pressure amplitudes respond linearly to dust loading? For the gradual changes, we shall test if they can be accounted for by changes in properties of thermal tides that have been reported or predicted by previous workers. For instance, the amplitude of DK1 is particularly strong during early northern summer, but declines significantly by the fall equinox (Wilson and Hamilton, 1996; Haberle et al., 2014).

During this work, we shall pay attention to possible effects of Curiosity's location within Gale crater on the state of the atmosphere. Many other scientists working with Curiosity data are also interested in this issue (e.g., Tyler and Barnes, 2013; Haberle et al., 2014). We shall reach out to Mars scientists working in this area and leverage collaborations with them to understand how local effects may obscure the signatures of larger-scale tidal activity. Our contribution to this community-wide activity will be the identification of any major inconsistencies between tidal effects in Curiosity's pressure data and tidal effects in MCS temperature profiles (**Tasks B and C**). If seen, such inconsistencies will suggest that the local view from within Gale crater differs from the global-scale view of MCS due to local effects on atmospheric conditions at Curiosity.

7. Task B: Effects of thermal tides on the atmospheric structure above Gale crater

This **Task** has three parts. To prepare for the first part, we shall use MCS data to construct vertical profiles of the day-night temperature difference above Gale crater. Over a range of seasons, we shall determine the vertical wavelength of oscillations in this temperature difference, the pressure levels of extrema in the oscillations, and the pressure-dependent amplitude of the oscillations. The second part will make use of zonal mean MCS profiles from the latitude of Gale crater and six local solar times. The third part will make use of zonal variations in the MCS day-night temperature difference at the latitude of Gale crater.

First, we shall pursue the migrating diurnal tide. We shall compare the vertical wavelength in MCS day-night temperature differences above Gale crater to that predicted for the migrating diurnal tide, expecting agreement when the migrating diurnal tide dominates. We shall compare the amplitude of the oscillations to the amplitude of the diurnal component of Curiosity's pressure variations, expecting correlation when the migrating diurnal tide is strong. We shall compare pressure levels of extrema in the oscillations to the phase of the diurnal component of Curiosity's pressure variations, expecting extrema to rise/fall as the phase advances/retreats when the migrating diurnal tide dominates. Deviation from these expectations will indicate the presence of other tidal modes, such as the migrating ter-diurnal tide or non-migrating tidal modes like DK1. The details of how the results deviate from expectations will constrain which other tidal modes are present. If the amplitude found by this analysis of profiles from above Gale crater is weak, then we shall repeat this activity with improved statistics using the zonal mean day-night temperature difference. This also contains the signature of the migrating diurnal tide.

Second, we shall pursue the migrating semi-diurnal tide, to which the day-night temperature difference addressed in the previous paragraph is not sensitive. Inspired by Kleinbohl et al. (2013), initially we shall harmonically decompose zonal mean MCS temperature profiles at the latitude of Gale crater at six local solar times (Fig. 12) in order to determine the amplitude and phase of the migrating semi-diurnal tide as functions of altitude (pressure) and season. Higher-order migrating tides may also be detected, but the limited and concentrated coverage in local solar time will make that challenging. As for the migrating diurnal tide, we shall compare the characteristics of the migrating semi-diurnal tide in MCS data to characteristics of the semi-diurnal variation in Curiosity's pressure data, guided by expectations from classical tidal theory. Deviations from expectations will constrain which other tidal modes might be present. Note that this activity will also probe the migrating diurnal tide, which was the focus of the first activity of this **Task**. Nevertheless, we retain the first activity of this **Task** since it provides a very well-defined starting point with clear heritage from previous work by others (e.g., Lee et al., 2009).

Third, we shall pursue non-migrating tidal modes. Following Guzewich et al. (2012), we shall use zonal variations in vertical profiles of the day-night temperature average and the day-night temperature difference at Curiosity's latitude (Fig. 8). Different harmonic components of these two temperature composites are affected by different non-migrating tidal modes. For example, the wave-2 (2 maxima per 360^{o} of longitude) component in the temperature difference is affected by DK1. We shall use the zonal variations to measure the amplitudes and phases of the strongest non-migrating tidal modes and test if these results, the MCS results for the migrating diurnal and semi-diurnal tides, and the components of Curiosity's pressure variations are consistent.

8. Task C: Effects of thermal tides on meridional variations in the atmosphere

Task B will have reached conclusions about the characteristics of the main migrating and non-migrating tidal modes at the latitude of Gale crater. The implications of these conclusions for the meridional structure of the atmosphere will be tested in **Task C**.

The second part of **Task B** investigated the zonal mean MCS temperature as a function of local time, thereby probing migrating tidal modes, whilst the third part investigated zonal variations in the MCS day-night temperature average and difference, thereby probing non-migrating tidal modes. In this **Task**, these two activities will be extended to all latitudes so that the vertical wavelengths, amplitudes, and phase of different migrating and non-migrating tidal modes can be determined as functions of latitude, altitude, and season (Fig. 5). Since each tidal mode has a distinctive meridional structure, we shall use the resulting patterns to test the conclusions reached in **Task B** (equatorial observations only) concerning which tidal modes are strongest.

Finally, we shall compare the global-scale behavior of thermal tides found by these analyses of the MCS data to tidal predictions by the Mars Climate Database (Lewis et al., 1999) in order to see how well the observed behavior fits into the context of present knowledge of the atmosphere. Major differences between observations and model will highlight issues of potential importance.

9. Broader impacts

At the end of the proposed work, we will have placed the effects of thermal tides on conditions within Gale crater within the context of the global-scale behavior of thermal tides. In addition, we will have firmly connected two complementary effects of thermal tides: variations with local solar time in observations at a fixed longitude and variations with longitude in observations at a fixed local solar time. Finally, we will have tested the ability of a widely-used general circulation model, the Mars Climate Database, to accurately predict the full range of effects of thermal tides.

This proposed work, which will train a female postdoctoral researcher, will increase the participation of women in science and will contribute to the development of a diverse, globally competitive STEM workforce. The proposed testing of the Mars Climate Database, which plays an important role in many studies of the environment of Mars, will enhance infrastructure for research. The improved understanding of thermal tides on an Earth-like planet that is not Earth will be of interest to terrestrial atmospheric scientists, since thermal tides are also important in Earth's climate. The increased interaction between planetary and terrestrial atmospheric scientists that this proposed work will stimulate will also enhance infrastructure for research.

We plan to produce one peer-reviewed manuscript per year during the course of this project, one for each **Task**. The amplitudes and phases of harmonic components fitted to Curiosity pressure data in **Task A** may be useful to other researchers, and so we shall make them available as supplemental information to our published papers

10. Personnel and work plan

This proposed work will be carried out by PI Paul Withers and postdoctoral researcher Christina Holstein-Rathlou. We plan to produce one peer-reviewed manuscript per year.

PI Paul Withers will be responsible for the success of this investigation and for compliance with all reporting requirements. He has completed a range of studies on the atmosphere of Mars, including the effects of thermal tides on atmospheric entry data, temperature-pressure profiles, and thermospheric conditions (Withers et al., 2003, 2011; Withers and Smith, 2006; Withers and Catling, 2010; Withers and Pratt, 2013). He will supervise postdoc Holstein-Rathlou, who will perform most of the proposed activities. His level of effort will be 0.5 summer months per year. In addition, during the academic year "NSF regards research as one of the normal functions of faculty members at institutions of higher education." (Grant Proposal Guide, page II-14).

Postdoctoral researcher Christina Holstein-Rathlou will be responsible for analysis of Curiosity pressure data and MCS temperature-pressure profiles, plus manuscript preparation. She has worked on operations and analysis of data from the Phoenix meteorological suite and from Curiosity's atmospheric entry (Holstein-Rathlou et al., 2010, 2012, 2014a, b; Holstein-Rathlou and Withers, 2014a, b). Her level of effort will be 9 months per year. The budget includes one conference trip per year for Holstein-Rathlou, which is needed to support her professional development and for receiving critical feedback from colleagues on work in progress.

Task A	**Effort**	**Year**
Determine amplitudes and phases of the diurnal to quad-diurnal harmonics in Curiosity's pressure data as a function of season (Sections 3.1 and 6)	1 m	1
Compare these results to Mars Climate Database predictions (Section 6)	1 m	1
Correlate characteristics of tidal variations in surface pressure with dust content (Section 6)	1.5 m	1
Investigate short-lived changes in characteristics of tidal variations in surface pressure (Section 6)	1 m	1
Investigate longer-lived, abrupt changes in surface pressure tides (Section 6)	1.5 m	1
Investigate longer-lived, gradual changes in surface pressure tides (Section 6)	1.5 m	1
Prepare manuscript describing results from **Task A**	1.5 m	1

Task B	**Effort**	**Year**
Characterize migrating diurnal tide using MCS profiles at Curiosity's latitude (Sections 3.2 and 7)	2 m	2
Characterize all migrating tides using MCS profiles at Curiosity's latitude (Sections 3.2 and 7)	2.5 m	2
Characterize non-migrating tidal modes using MCS profiles at Curiosity's latitude (Sections 3.2 and 7)	2.5 m	2
Prepare manuscript describing results from **Task B**	2 m	2
Task C	**Effort**	**Year**
Characterize all migrating tides using global coverage of MCS profiles (Sections 3.3 and 8)	2.5 m	3
Characterize non-migrating tidal modes using global coverage of MCS profiles (Sections 3.3 and 8)	2.5 m	3
Place results in context of Mars Climate Database predictions (Section 8)	2.5 m	3
Prepare manuscript describing results from **Task C**	1.5 m	3

Table 2. Work plan with activities in chronological order. Effort is that of Holstein-Rathlou.

11. Results from prior NSF support

(a) Award: AST-1211490 (PI Withers) $294K 2012.08.15 – 2015.07.31
(b) Title: The ionosphere of Venus
(c) Summary of work:
(Intellectual Merit) We have produced a listing of the physical properties (density, height, width) of the two main ionospheric layers from Venus Express radio occultation observations, and prepared a manuscript analyzing the behavior of Venus's analog to the M1 layer that was distributed to coauthors in summer 2014. We have also characterized sporadic layers of plasma associated with meteoroid ablation in preparation for the first manuscript describing the properties of these layers on Venus. We have used archived in situ data from the Pioneer Venus mission to identify major weaknesses in the Venus International Reference Ionosphere. Finally, we have recovered the Pioneer Venus radio occultation electron density and neutral atmospheric profiles, which had been lost for decades.
(Broader Impact) The findings concerning the behavior of the layers of the Venus ionosphere will be beneficial for researchers studying the ionospheres of other planets. The identification of major weaknesses in the planet's reference ionosphere will impact many ongoing studies of the space environment of Venus and the interpretation of many past publications. The recovered Pioneer Venus radio occultation data will be immensely valuable to researchers. Much of this work has been performed by two undergraduates mentored by two graduate students.
(d) Publications: No manuscripts have been published yet, although a manuscript concerning the weaknesses in the reference ionosphere has been distributed to coauthors and a manuscript concerning the behavior of the main ionospheric layers was distributed to coauthors in summer 2014. Presentations have been delivered at several conferences and workshops.
(e) Research products: The Pioneer Venus radio occultation data were only recovered only a few months ago, and plans for their archiving and preservation are being developed at this time. Other research products will be made available via publications.
(f) Completed and proposed work: N/A for non-renewal proposals.