



## Oscillation of Venus' upper atmosphere

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[1] Little is known about the variability of Venus' upper atmosphere. We report discovery of a large ( $\sim \pm 30\text{--}50\%$ ) 9-day period density oscillation, derived from radar tracking of the Magellan spacecraft from 15 Sept 92 – 24 May 93. The densities correspond to 164–184 km altitude, 11°N latitude, and cover all local times. The wave is presumed to propagate upward from lower atmosphere regions, and occurs mainly between dusk and midnight, suggesting that local time differences in forcing and/or mean wind filtering are affecting accessibility to the upper atmosphere. Possible sources for the wave are discussed, including wave-wave interactions. Many questions remain concerning the origin and nature of the 9-day oscillation, including its persistence. Instruments on Venus Express, now orbiting Venus, have the opportunity to further elucidate the 9-day wave and understand its role in the dynamics of Venus' upper atmosphere. **Citation:** Forbes, J. M., and A. Konopliv (2007), Oscillation of Venus' upper atmosphere, *Geophys. Res. Lett.*, *34*, L08202, doi:10.1029/2007GL029252.

### 1. Introduction

[2] Planetary atmospheres are rotating, vertically-stratified fluids in a spherical geometry, and thus support a variety of wave motions peculiar to these conditions [Longuet-Higgins, 1968]. Earth's and Mars' atmospheres co-rotate with their respective planets and at nearly the same rates. Venus is unusual in that the planet rotates with a sidereal period of 243 Earth days and in the retrograde direction, but the atmosphere rotates nearly 60 times as fast, at least near the cloud tops (ca. 65 km altitude) where most observational data pertain [Schubert, 1983]. Evidence for super-rotation also exists at altitudes above 100 km [Alexander, 1992], i.e., in the thermosphere. Super-rotation is likely driven by deposition of momentum due to dissipating atmospheric waves, including solar thermal tides, Kelvin waves, Rossby waves and possibly gravity waves [Forbes, 2002]. An understanding of wave motions in Venus' atmosphere is thus critical to understanding its general circulation as well as its variability.

[3] Herein we report discovery of a 9-day density oscillation in the thermosphere of Venus. Most observations of waves in Venus' atmosphere are derived from the movement of clouds near 65 km [Del Genio and Rossow, 1982, 1990; Rossow *et al.*, 1990] with a few other observations between 65 and 90 km [Apt and Leung, 1982; Taylor *et al.*, 1980]. These data generally indicate existence of a low-

latitude Kelvin wave with period  $\approx 4$  days, and a mid-latitude Rossby wave with period  $\approx 5\text{--}6$  days. A secondary oscillation at 2.6 days is observed [Del Genio and Rossow, 1982] at cloud tops, and a strong 2.9-day period wave is reported [Apt and Leung, 1982] at 70–80 km that may correspond to the 2.7-day wave predicted [Covey and Schubert, 1982] to be a “preferred response” of Venus' atmosphere. Thus, a 2.6–2.9 day wave remains a real possibility as a characteristic wave period in Venus' atmosphere. As we show below, this wave may provide a clue to existence of a 9-day periodicity in Venus' atmosphere.

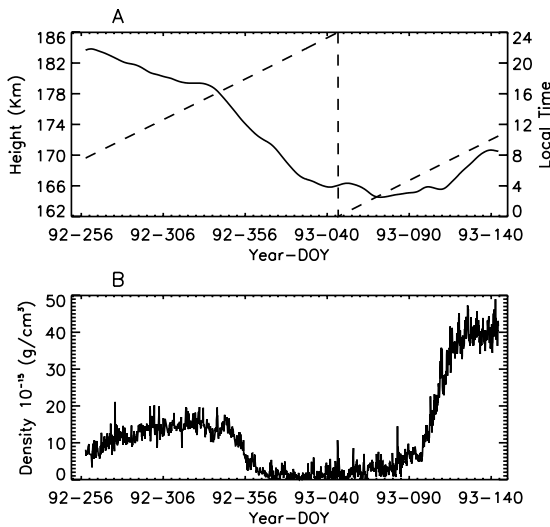
### 2. Data Analysis

[4] Densities are derived from high-precision orbit determination of the Magellan spacecraft between 15 Sept 92 – 24 May 93, covering one complete rotation of Venus. Periapsis ( $h_p$ ) remained near 11°N latitude and sufficiently low (164–184 km) that atmospheric density produced measurable orbital changes from orbit to orbit. We processed S-band and X-band Deep-Space Network (DSN) Doppler tracking data in arcs of about 1 day and 3 days in length using the JPL Orbit Determination Program (ODP) [Moyer, 1971], and found the 3-day arcs to provide significantly reduced uncertainties in the derived densities. The latest high resolution Venusian gravity model MGNP180U of spherical harmonic degree 180 [Konopliv *et al.*, 1999] was used and provides the smallest scatter in the density solutions. For each arc, the estimated parameters are: epoch position and velocity, velocity corrections in all three directions for the angular momentum wheel maneuvers that occurred every orbit, three solar pressure coefficients per arc (one for each direction), and an atmospheric density every orbit (about every 3.2 hours). Density uncertainties were computed each orbit from a least-squares estimation process where the Doppler data were noise-weighted for each DSN tracking pass.

[5] Densities at  $h_p$ , local time, and  $h_p$  for Magellan are displayed in Figure 1. The densities vary considerably due to altitude and local time effects. To isolate the variability at shorter time scales, densities were normalized to 170 km using Hedin *et al.*'s [1983] model and an 11-day running mean calculated to establish remaining trends due to unmodelled variations (see Figure 2a for nighttime data). Residuals from the trend were then subjected to Lomb-Scargle Periodogram (LSP) [Lomb, 1976; Scargle, 1982] analysis, revealing a predominant oscillation above the 99% confidence level at 9-day period at night (Figure 3) and 10-day period during the day (not shown). To focus on the variability near 9-day period and prepare the data for filtering, daily mean density residuals were computed every 0.25 days (shown in Figure 2b for nighttime data), and the resulting data band-pass filtered to arrive at our final result

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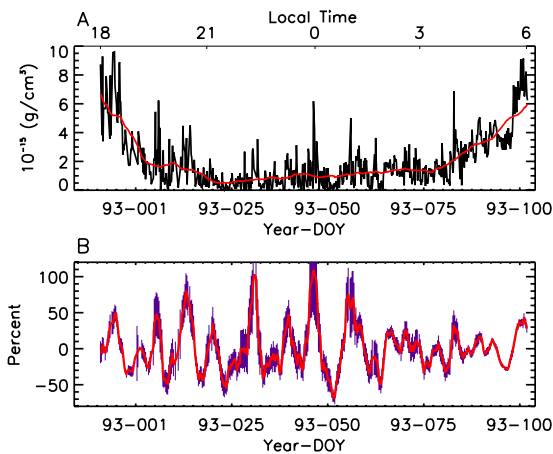


**Figure 1.** (a) Height (solid curve) and local time (dashed curve), and (b) raw total mass densities ( $10^{-15} \text{ g cm}^{-3}$ ), at periaapsis versus time.

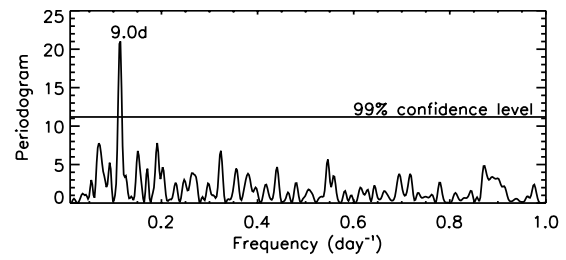
in Figure 4. The oscillations are large,  $\pm 30$ – $50\%$  of background level, and mainly confined to the 1700–0300 local time sector. Appearance of the wave at these amplitudes is not well correlated with altitude of measurement (cf. Figure 1). A secondary peak at 4.7-day period also appeared in the daytime data, near the 99% confidence level. However, since the relative density oscillations are so much smaller during the day, we focus here on variability at 9–10 day period that is predominant during all local times. We now briefly explore the possible origins and implications of the observed wave features.

### 3. Analysis and Interpretation

[6] Apart from vertical propagation characteristics, the atmospheric oscillations of interest can be expressed as



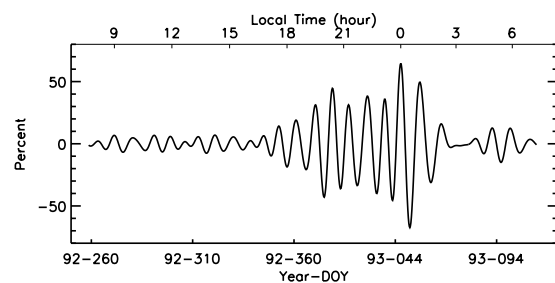
**Figure 2.** (a) Orbit-by-orbit nighttime densities ( $10^{-15} \text{ g cm}^{-3}$ ) normalized to 170 km (black), and 11-day running means (red) versus day of year (1992–1993) and local time. (b) Daily averages of density residuals from running mean in Figure 2a, at 0.25-day resolution. Vertical lines in Figure 2b represent 1-sigma uncertainty estimates.



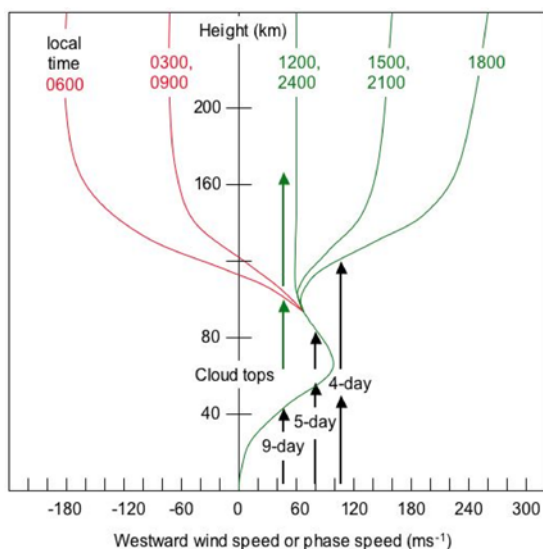
**Figure 3.** Lomb-Scargle periodogram of residuals from 11-day running mean of nighttime densities (Figure 2a), illustrating a single peak at 9-day period well above the 99% confidence level.

$A \cos(\sigma t + s\lambda - \phi)$  where  $t$  = time (days),  $\sigma = \frac{2\pi}{T}$ ,  $T$  is the wave period in days,  $\lambda$  = longitude (positive westward for Venus),  $s$  ( $= \dots -3, -2, \dots, 0, 1, 2, \dots$ ) is the zonal wavenumber, and the amplitude  $A$  and phase  $\phi$  are functions of height and latitude. The zonal (east-west) phase velocity is  $C_{ph} = -\frac{\sigma}{s}$ , and westward (eastward) propagation corresponds to  $s < 0$  ( $s > 0$ ). From the perspective of the periaapsis of Magellan,  $\lambda \approx$  constant over 9 days, and therefore the measured wave period is very nearly the true wave period (i.e., from the ground-based perspective). However, it is not possible from our observations to distinguish whether the wave structure in Figure 4 is zonally symmetric ( $s = 0$ ), eastward- or westward propagating, or is representative of a superposition of various waves near 9-day period. We consider several possibilities below.

[7] Why an oscillation at 9-day period? One possibility is nonlinear interaction between two other waves, analogous to similar occurrences in Earth's upper atmosphere [e.g., Pogoreltsev *et al.*, 2002]. Numerical simulations indicate that nonlinear interaction between waves with periods of 4 days and 5.7 days can generate a zonally-symmetric ( $s = 0$ ) 13.4-day oscillation in Venus' atmosphere [Yamamoto and Tanaka, 1997]. A possible wave-wave interaction producing a 9-day oscillation is between the aforementioned 4-day and 2.8-day waves, leading to a zonally-symmetric ( $s = 0$ ) 9.3-day wave and an  $s = 2$  1.6-day wave. The former is very close in period to what we see, and the latter is at too high frequency to be revealed in our data. Excitation may preferentially occur above cloud tops where wave amplitudes are sufficiently large to interact nonlinearly, thus explaining absence of any previous detection. Other possible



**Figure 4.** Band-pass filtered density residuals, percent of 11-day running mean. The band-pass filter was centered at a frequency of  $0.11 \text{ day}^{-1}$ , with half-power points at  $0.08 \text{ day}^{-1}$  and  $0.14 \text{ day}^{-1}$ .



**Figure 5.** Schematic of wind profiles in Venus' atmosphere and effects on vertical propagation of several waves, assuming  $s = 1$ . Profiles above 110 km are based on model simulations [Bougher *et al.*, 1988] consistent with available observations. Winds at lower altitudes [Schubert, 1983; Lellouch *et al.*, 1997; Alexander, 1992] are based on sparse information, especially between 70–110 km. Profiles in this height region are drawn to smoothly transition from the peak at 65 km to values above 110 km. Vertical arrows indicate upward propagating waves with periods near 4 days ( $C_{ph} \approx 106 \text{ ms}^{-1}$ ), 5 days ( $C_{ph} \approx 85 \text{ ms}^{-1}$ ), and 9 days ( $C_{ph} \approx 43 \text{ ms}^{-1}$ ), forced near the surface or the cloud tops. A 9-day wave can propagate to Magellan altitudes between about 1200–2400 LT, but the 4- and 5-day waves are likely to reach critical levels at lower heights.

sources of excitation are atmospheric resonance or baroclinic instability [Schubert, 1983]. None of the above mechanisms have been explored theoretically or in a modelling context for the 80–150 km region of Venus' atmosphere.

[8] Why the restriction to certain local times, or equivalently, solar longitudes? One possibility is that this is a transient event, and that the wave does exist at all longitudes from day 350 of 1992 (LT  $\approx 1700$ ) through day 70 of 1993 (LT  $\approx 0300$ ). Alternatively, the wave may be confined to these local times and longitudes due to variations in excitation, dissipation, or interactions with background mean winds. In this case, the 9-day oscillation observed by Magellan may represent superposition of 9-day waves of several zonal wavenumbers that constructively and destructively interfere to produce the impression of transience or confinement seen in Figure 4. Similar longitude variations are known to exist for terrestrial atmospheric tidal oscillations [e.g., Cierpik *et al.*, 2003] generated through wave-wave interactions. We now explore several possible mechanisms that can restrict the 9-day oscillation to specific longitudes or local times.

[9] Thermosphere densities are smallest at night (cf. Figure 1) due to the extremely cold temperatures imposed by  $\text{CO}_2$  radiative cooling in the absence of solar radiative heating. Day-night differences in density translate to differences in exponential growth of a vertically-propagating

wave, the altitude at which exponential growth ceases due to dissipation, and the rate of decrease of wave amplitude above the peak [Yanowitz, 1967; Lindzen, 1970]. The first two of these effects tend to cancel out, and the third favors higher wave amplitudes during day than night. Therefore, molecular dissipation effects cannot explain the day-night differences in amplitude seen in Figure 4. Differing mean thermal and wind structures between day and night could affect the generation of waves arising from resonance or instability, and this remains a possibility. Radiative damping of upward-propagating waves may be more efficient during daytime, when  $O/\text{CO}_2$  density ratios are higher. Numerical modelling work is required to quantify these mechanisms. However, it can be stated that diurnal variations in wave driving or dissipation cannot explain the abrupt cessation of wave amplitudes seen in Figure 4 after midnight. Therefore we seek an alternative explanation in terms of mean wind filtering effects.

[10] If one considers the vertical profiles of westward wind for low latitudes, combined with the fact that upward-propagating waves cannot pass through a “critical level” where the zonal wave phase ( $C_{ph}$ ) and mean wind ( $U$ ) speeds are equal, then constraints can be placed on accessibility of the 9-day wave to Magellan heights. Figure 5 shows that if the 9-day wave has  $s = 1$  and is forced at the cloud tops or above, then propagation to Magellan heights is possible only within the local time window  $\approx 1200$  LT to  $\approx 2400$  LT. Cessation of wave activity just after midnight (cf. Figure 4) can therefore be plausibly explained in terms of wind filtering effects assuming  $s \neq 0$ ; however the onset of wave activity cannot.

[11] It can be argued that a 9-day  $s = 1$  wave is vertically-propagating. Such a wave has an equatorial westward phase speed of  $43 \text{ ms}^{-1}$ , and thus propagates in the retrograde direction (eastward) with respect to the mean flow. For the super-rotation rates depicted in Figure 5, Doppler-shifted phase speeds  $\sim 20$ – $60 \text{ ms}^{-1}$  are implied. These phase speeds are consistent with an  $s = 1$  vertically-propagating Rossby wave with vertical wavelengths  $\sim 30$ – $60 \text{ km}$  [Del Genio and Rossow, 1990]. Of course, a dilemma arises in that the above arguments assuming  $s = 1$  do not apply to the zonally symmetric ( $s = 0$ ) oscillation previously hypothesized to arise from nonlinear interactions, and invoked to explain the observed 9-day periodicity.

[12] A previous study [Keating *et al.*, 1979] inferred existence of a 5.7-day oscillation from *visual analysis* of densities and temperatures derived from drag analyses of Pioneer Venus Orbiter (PVO). However, that study did not mention that many of those data were acquired when the periapsis of PVO was oscillating up and down with a period near 7 days; periapsis drifted upward due to the effects of solar gravity, and was adjusted downward by spacecraft thrusting to make possible in-situ measurements in this atmospheric regime by other instruments on PVO. We obtained these data from the NASA NSSDC Master Catalog (<http://nssdc.gsfc.nasa.gov/database/MasterCatalog?ds=PSPA-00109>), and analyzed them using the same methodologies employed here. We could not definitively separate the artificial oscillations near 7-day period due to changes in periapsis height from any natural oscillations that might have occurred. Moreover, during a period of time (days 58–105 of 1979) when changes in  $h_P$  were smooth during the

time period analyzed by Keating *et al.* [1979], we found the dominant period of density variability to be near 9 days, but below the 95% confidence level. *Therefore, the only existing conclusive evidence for short-term cyclic variations in Venus' thermosphere points to a 9-day oscillation.*

#### 4. Conclusions

[13] The present paper establishes existence of a 9-day oscillation in Venus' thermosphere, a wave significantly different in period than the quasi- 4- and 5-day waves that characterize the cloud tops. The wave is restricted to local times of 1700-0200 LT. Amplitudes are relatively large, and modeling work is needed to determine whether dissipation of the wave can deposit sufficient westward momentum to drive super-rotation of Venus' thermosphere [Alexander, 1992]. The restrictive atmospheric sampling precludes definitive determination of the zonal wavenumber of the oscillation. Possible location of the source region well above the cloud tops and/or non-persistence of the oscillation may explain the absence of previous detections. Interaction with the mean circulation may determine accessibility of the wave to thermosphere altitudes during certain local times. Venus Express arrived at Venus in April, 2006, and is currently acquiring a variety of measurements throughout the atmosphere pertinent to the present work. Our results pose a challenge to the Venus Express Mission to further elucidate the 9-day wave, and to address the questions raised here concerning its origins, characteristics and overall role in the dynamics of Venus' upper atmosphere.

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