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Exploring the Phase of Venus's Thermal Tides Using a GCM

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Abstract

Venus's slow rotation and dense atmosphere host thermal tides, which are periodic variations in atmospheric temperature, pressure, and wind patterns forced by the variation in the absorption of solar radiation from day to night. These tides also manifest as surface pressure and temperature anomalies that migrate in response to the planet's solar forcing, as seen from Venus General Circulation Model (GCM). Variations in surface pressure and atmospheric mass distribution contribute to measured gravity anomalies. Gravity measurements are important in studying the mass distribution and internal structure of Venus. Since the pressure anomalies are driven by mass redistribution, the atmospheric mass redistribution should be taken into account and studied, to have a full and comprehensive understanding of the gravity measurements.

Using the LMD Venus General Circulation Model (GCM), we explore the structure and phase of the surface pressure anomalies and their dependence on solar day length (SD). Results suggest a phase shift in surface pressure anomalies from the sub-solar longitude, linked to a radiative time scale of ~10 days, potentially governing the atmospheric response to solar heating. By varying SD through changes in orbital period and rotation rate, we identify an inverse relationship between the anomaly phase and SD. Simulations near a 1:2 resonance between SD and the radiative time scale reveal amplified anomalies, supporting the hypothesis of resonance effects.

Manifestation of Thermal Tides in Surface Pressure Anomalies

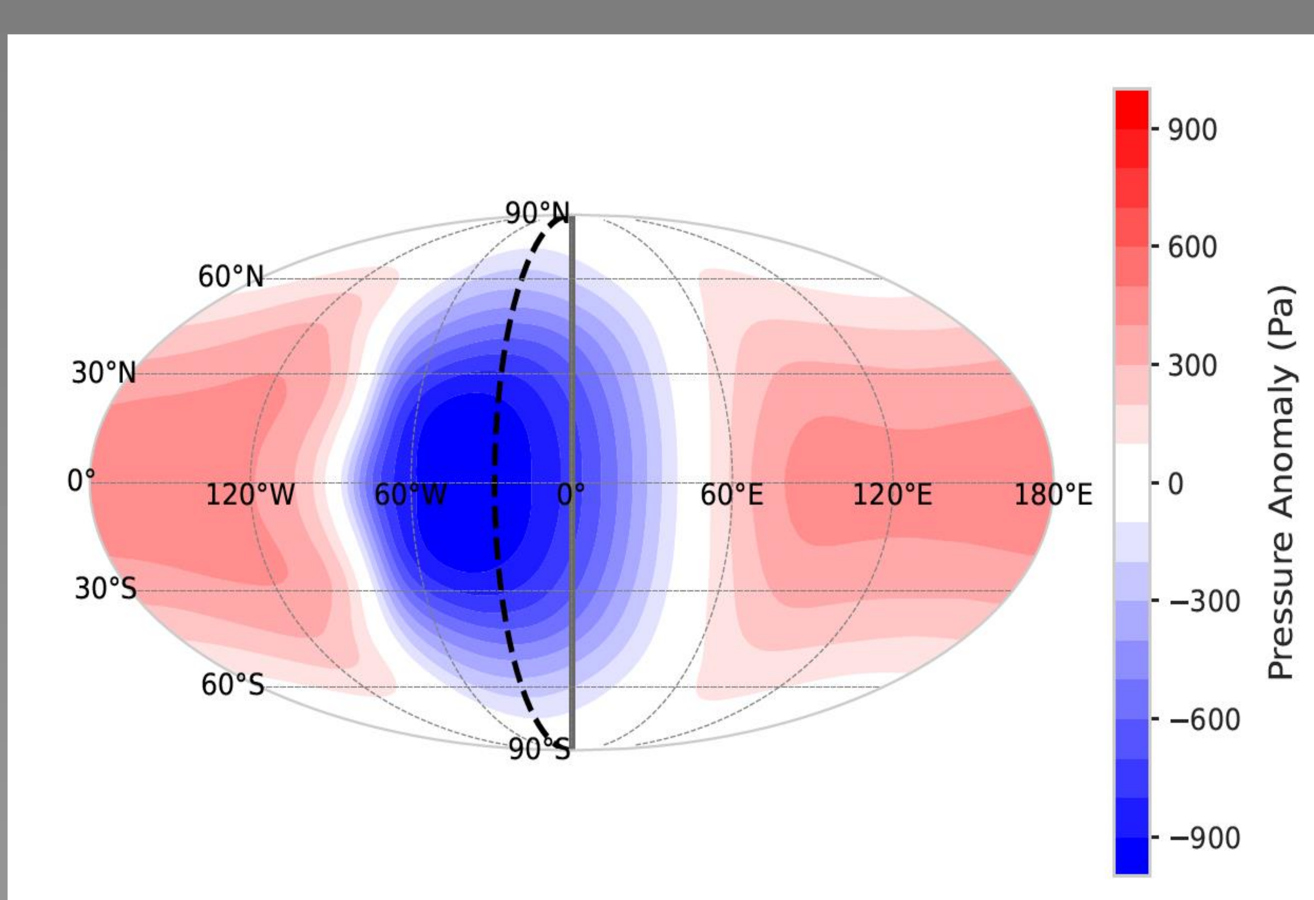


Fig. 1 Mean thermal tide surface pressure anomaly, from a solar-fixed reference frame. The Sun is positioned at the origin, with a latitude 0° and longitude of 0° (grey bold line). The dashed black line is positioned in longitude of 28.8°. The colorbar indicates the surface pressure anomaly in Pa units.

Venus Orbit and Rotation

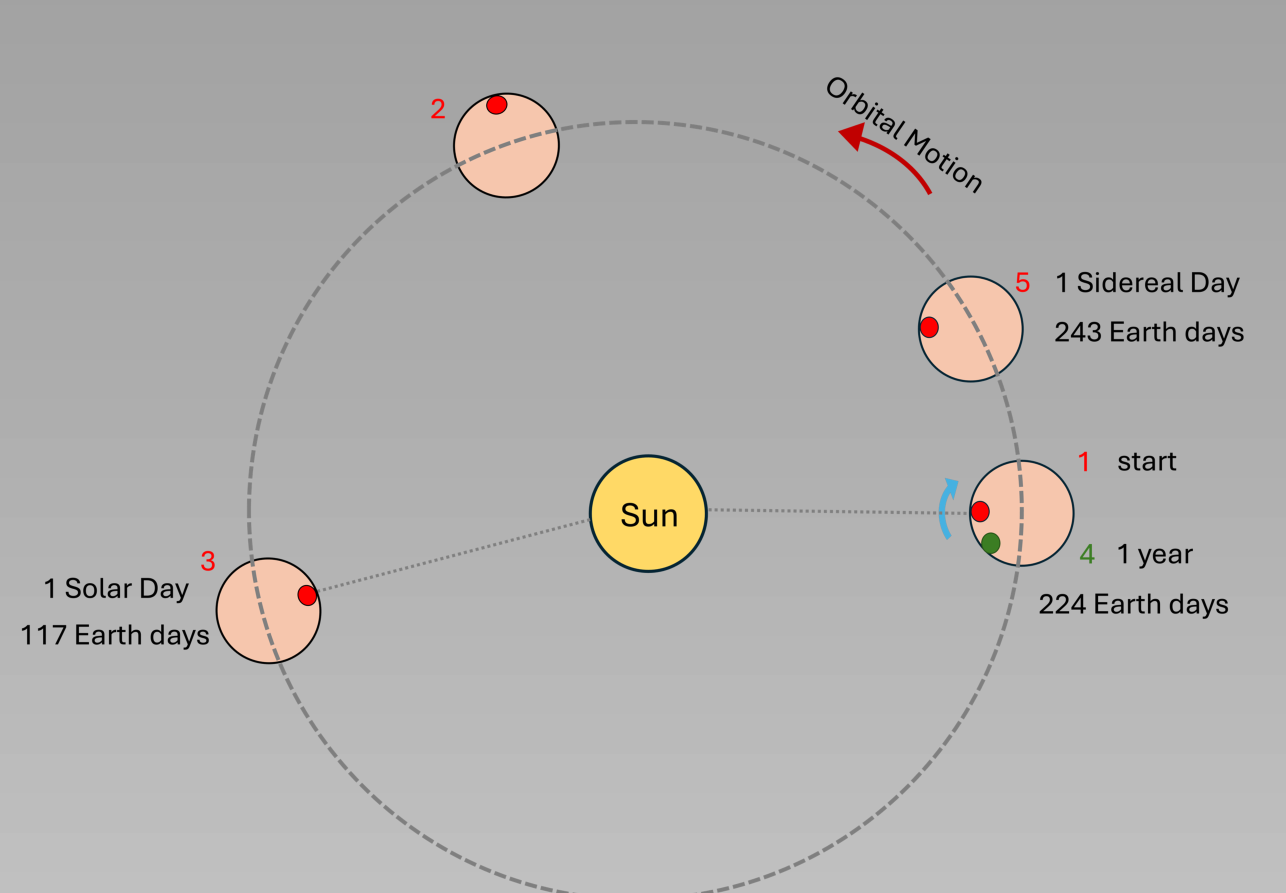


Fig. 2: An illustration of the orbital constants of Venus. Venus rotates in the opposite direction of its orbit around the Sun, meaning its rotation is retrograde. The red spot represents a constant position on Venus's surface. The numbers indicate chronological steps in Venus's orbit.

Methods

We used the LMD Venus GCM, featuring 96×97 horizontal grid points and 50 vertical levels up to 100 km altitude. Simulations were initialized with a flat surface, superrotating atmosphere, and 92-bar surface pressure, running for 20 Venusian days to reach a steady state. Thermal tides were analyzed in surface pressure anomalies in a solar-fixed reference frame.

The thermal radiative timescale (τ_R) quantifies the atmosphere's response to solar forcing and is defined as:

$$\tau_R = \frac{MC_p}{4\sigma T_e^3}$$

where M is the atmospheric mass per unit area, C_p the specific heat at constant pressure, σ the Stefan-Boltzmann constant, and T_e the effective temperature. The phase of thermal tides (Φ) relative to the sub-solar longitude is governed by through τ_R:

$$\tau_R = \frac{\Phi}{2\pi} \times \text{Solar day}$$

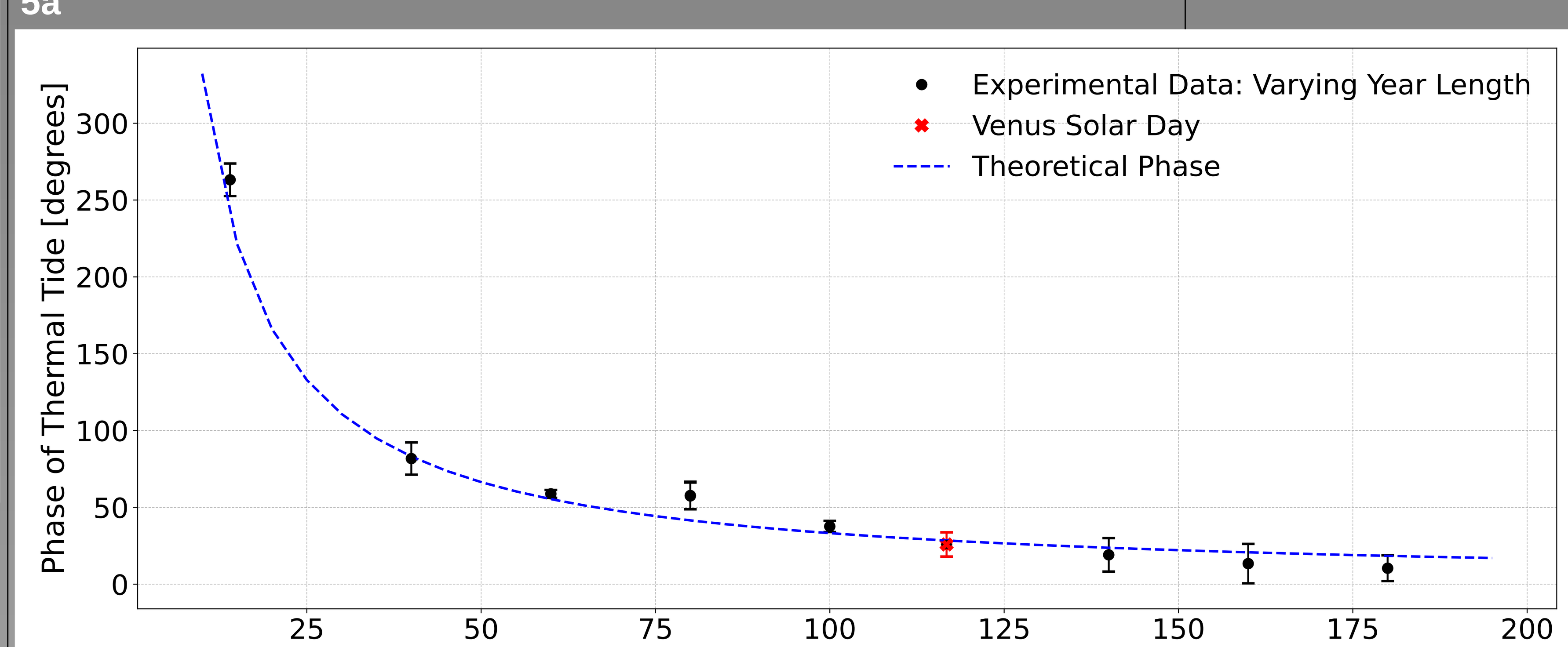
Combining the two equations, the connection of the thermal tide phase to the solar day can be described by the following analytical expression:

$$\Phi = \tau_R \cdot \frac{2\pi}{\text{Solar day}}$$

Results

In order to validate our hypothesis regarding the radiative timescale setting the phase of the thermal tide, we study how the phase of the thermal tide changes when the length of the solar day on Venus is varied. Two approaches were used to modify the solar day length: 1) Altering the orbital year length, which changes the frequency of the thermal forcing, and 2) Changing the rotation period (sidereal day) directly, which has a more substantial impact on the dynamics. According to the theoretical relationship linking τ_R, the solar day, and the thermal tide phase, the expected τ_R is ~9.4 days.

5a



5b

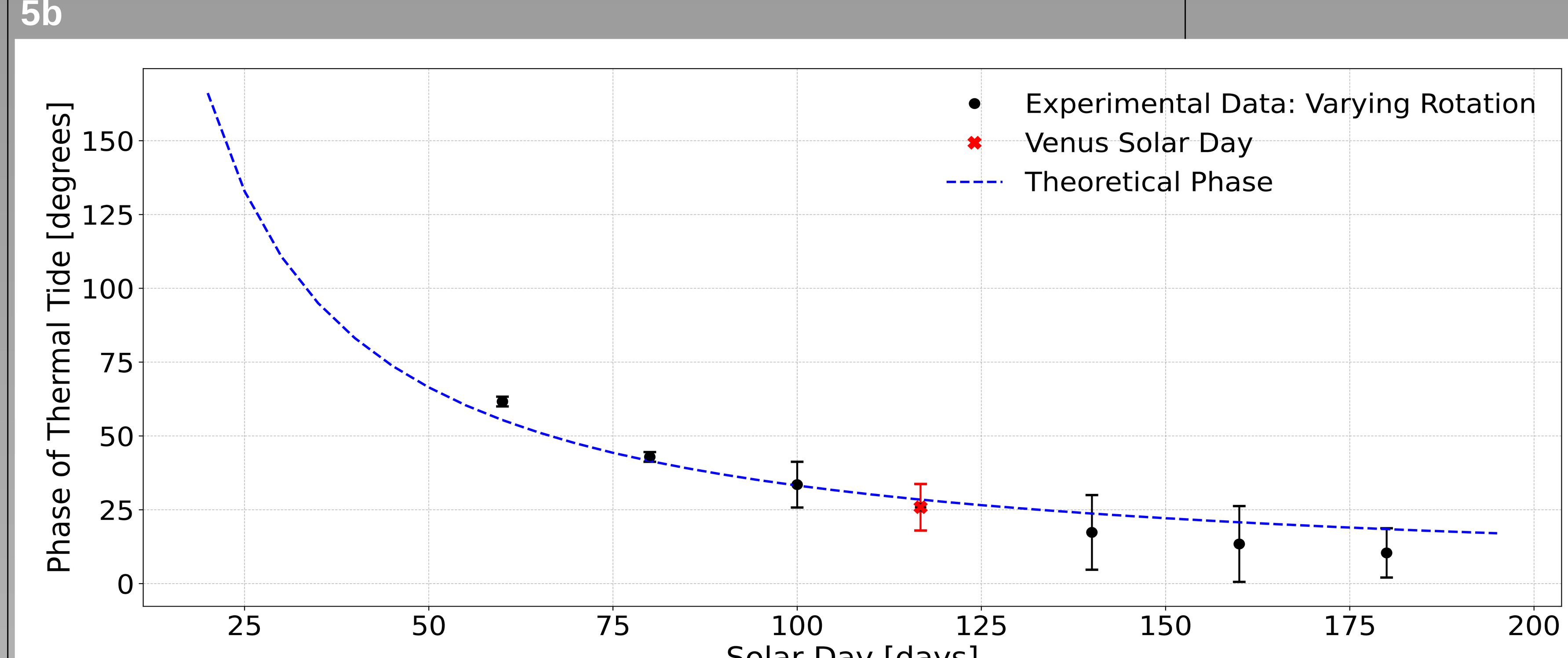


Fig. 5: The longitudinal phase of the thermal tide as measured from the surface pressure anomaly relative to the sub-solar point. The solar day length is varied by **(a)** changing the orbital period, and **(b)** changing the rotation rate. The red mark represents Venus's true solar day. The theoretical value assumes a radiative timescale of $\tau_R = 9.4$ Earth days. Each simulation ran for 20 Venusian solar days, with the plotted pressure field being the average over the final 3 days.

Resonance

4.

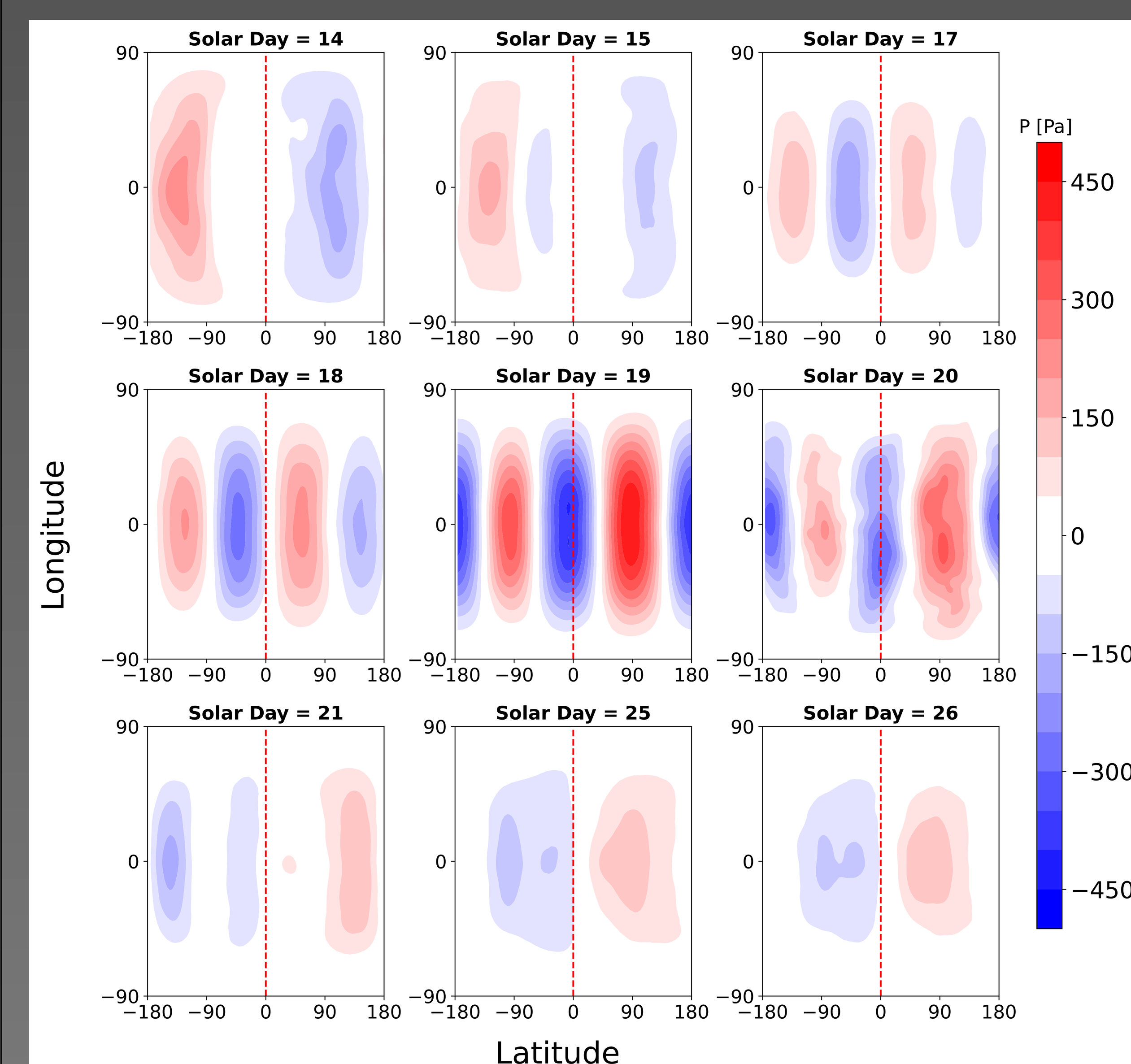


Fig. 4: The mean thermal tide pattern in surface pressure anomalies, viewed from a sub-solar perspective, for simulations with different solar day lengths. As the ratio between the atmospheric radiative timescale (τ_R) and the imposed solar day approaches 2:1, the thermal tide signal emerges twice. The strongest thermal tide amplitude is attained when the solar day period is set to 19 days. The red dashed vertical lines is the sub-solar longitude.

Conclusions

- An inverse relationship between the solar day length and the phase of surface pressure anomalies relative to the sub-solar longitude was observed, consistent with theoretical predictions $\left(\Phi \propto \frac{1}{SD}\right)$.
- Simulations near resonance, where the solar day is twice the radiative timescale, revealed amplified pressure anomalies, suggesting that this time scale is an important characteristic of the atmosphere of Venus.
- Future missions such as DAVINCI, VERITAS, and EnVision will include gravity measurements to study Venus's interior. Accounting for atmospheric mass transport in these measurements can help refine interior models while also providing insights into the dynamics in the atmosphere of Venus.