HARMONIC ANALYSIS OF VENUS' THERMAL TIDE. A. I. Ermakov[1] (eai@berkeley.edu), B.G. Bills[2], T. Navarro[3,4], G. Schubert[3], K. Górski[2]; [1]Space Sciences Laboratory, University of California, Berkeley, CA, 94720; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91011; [3]University of California, Los Angeles, CA, 90095; [4]McGill University, Montreal, Canada.

Introduction: The deep atmosphere of Venus contains most of its mass but is difficult to probe. For planets like Earth and Mars, with optically thin atmospheres, most of the solar radiation incident upon the top of the atmosphere reaches the surface. In contrast, for Venus, roughly 95% of the incident radiation is absorbed in the atmosphere [1]. At present, the depth dependence of that absorption is only poorly constrained since remote sensing does not accurately recover behavior beneath the cloud deck. For the same reason, the atmospheric circulation is also poorly constrained below the cloud deck. A handful of descent profiles are available from in-situ probes revealing that the angular momentum density peaks in the deep atmosphere, at an altitude of ≈20 km [2]. That deep part of the atmosphere can be probed by measuring gravitational signatures of the atmospheric thermal tide.

The atmospheric thermal tide has been proposed to play an important role in Venus' rotation history. The orbital period of Venus is ≈225 days. Venus rotates around its axis with a period of ≈243 days in the opposite direction with respect to its orbital motion. Consequently, the solar day on Venus is $\left(\frac{1}{225}+\frac{1}{243}\right)^{-1} \approx 116.7$ days. Shortly after early planetary radar studies revealed that Venus was not a synchronous rotator [3,4], it was suggested by [5] that the observed rotation state might represent a tidal torque balance. The Sun raises both gravitational time in its solid body and thermal tides in the atmosphere. The gravitational attraction from the Sun on the two tidal bulges yields two rather different tidal torques. The gravitational solid body tidal bulge is larger in amplitude but has a smaller phase lag. In contrast, the atmospheric thermal tidal bulge in the atmosphere is expected to have a small amplitude but a large phase lead. Therefore, the torques from the Sun acting on the two bulges can be equal in magnitude and of the opposite signs. This model for the origin of the rotation state of Venus has been widely supported by further analyses [6-9] but has not yet been tested by direct gravitational observations.

Motivation: Due to Venus' slow rotation, the figure of Venus is nearly a sphere. The hydrostatic contribution to J_2 is 25 times less than the measured value [10]. Therefore, the gravitational coefficient J_2 is not dominated by the hydrostatic component due to rotation and cannot be used as a constraint on the radial structure of the body. Seismic data is presently also not available, due to extremely hard surface conditions. Consequently, measurement of tides for Venus would provide an especially important constraint on the internal structure.

The strongest tidal perturbation on Venus is the Sun. Solar tides on Venus' have been measured by Pioneer Venus Orbiter and Magellan spacecraft but with a relatively low accuracy [10]. Potential tidal Love number k_2 was estimated to be 0.295 with 1σ of 0.033, which supported the hypothesis that Venus has a liquid core. Tidal phase lag, which is related to the dissipation within the body [11], has not been measured.

Future space missions (NASA's VERITAS and ESA's EnVision) will provide higher-resolution gravity data including the measurements of the tidal Love number k_2 and its phase lag [12,13]. VERITAS and EnVision are expected to measure the tidal phase lag to within 0.05° and 0.1°, respectively. These missions will also be sensitive to atmospheric gravity variations. Since the motion is spacecraft is simultaneously affected by both atmospheric and solid-body tide, Venus atmospheric time-variable signal would inevitably contaminate the solid-body tidal signal both in its magnitude and phase lag. For example, if Venus is in a state of torque balance, the effective tidal lag is zero. Thus, to enable interpreting the measurements of the observed tidal phase lag, we need to separate the atmospheric and solid body signals. Venus atmospheric gravity recovery is complicated by the slow rotation of Venus. For example, the Earth gravity mission GRACE could produce monthly solutions. This is facilitated by the fast rotation of the Earth: the spacecraft tracks can quickly cover the Earth. Venus' slow rotation leads to a very slow accumulation of spatial coverage, thus making it harder to distinguish spatial from temporal variations.

The goals of this study are: 1) to develop a realistic model of the atmospheric thermal tide based on the state-of-the-art Global Circulation Models of Venus; and 2) to examine how the thermal tide amplitudes and phases depend on poorly constrained parameters pertaining to global radiative transfer in the atmosphere.

Global Circulation Model (GCM): We used the same model setup as used in [14,15]. The GCM used for this study is the state-of-the-art, full physics, three-dimensional model developed at Institut Pierre-Simon Laplace [16,17]. It includes a finite differences dynamical core on a latitude-longitude grid and a realistic topography obtained from the Magellan mission [18]. The model resolution is 1.875° in latitude and 3.75° in longitude. Vertically, the atmosphere is split into 50 levels from the surface to 100 km. The physics parameterization uses the Mellor-Yamada boundary layer scheme [19]; a temperature-dependent formulation of the specific heat; a radiative transfer of gas and clouds using look-up tables to calculate heating rates split into contributions from the infrared and visible bands. The look-up table consists of net exchange rates matrices from correlated-k coefficients computed with a radiative transfer code [20]. Heat conduction in the ground is modeled with 11 layers from the surface to 12 m below the surface, assuming a vertically homogeneous subsurface [21].

Models of Thermal Tide: We use the surface pressure variations outputted from the GCM to develop a model of the thermal tide. It is convenient to consider surface pressure anomalies as they are related to the mass of the atmospheric column and can be converted to gravity anomalies. Bills et al. [15] modeled thermal tide with a rigid pattern model. In that model, the thermal tide amplitude is found by averaging surface pressure anomalies in the Sun-fixed frame. A rigid pattern of surface pressure anomaly is then rotated following the motion of the subsolar point. Surface pressure anomalies are then converted into gravity anomalies and time-variable contributions to the gravity coefficients. There are several drawbacks of such a model. First, it neglects the dependence of thermal tide on surface elevation. Second, the predicted variations of the degree 2 gravity coefficients have the same functional form as their variation due to the solid body tide, which would introduce a degeneracy in the determination of solid body and atmospheric thermal tidal parameters from the future gravity data.

An alternative thermal tide model employed in this paper is based on fitting harmonic series to surface pressure anomaly series:

$$\delta P(\Omega) = \sum_{l=1}^{N} A_l(\Omega)\cos(l(\lambda' - \theta_l(\Omega))), \quad (1)$$

where A_l are tidal amplitudes; θ_l are respective phase lags; λ' is the longitude in a Sun-fixed frame; and Ω denotes position on Venus' surface. A map of A_1 is shown in **Fig. 1.** It can be seen that A_1 correlates both with topography and latitude. For example, an outline of high-elevation Aphrodite Terra is visible as a region of a low thermal tide amplitude. In addition, high latitudes generally have lower values of A_1. The characteristic spatial pattern of A_1 makes it distinct of the solid-body tide, which is dominated by degree 2. Thus, this model of thermal tide would make it easier to separate gravitational signals from the thermal tide and the solid body tide. In our ongoing work, we examine how parameters A_l and θ_l depend on the assumed spatial variations of cloud top altitude, lower haze heating rate, surface roughness and thermal inertia.

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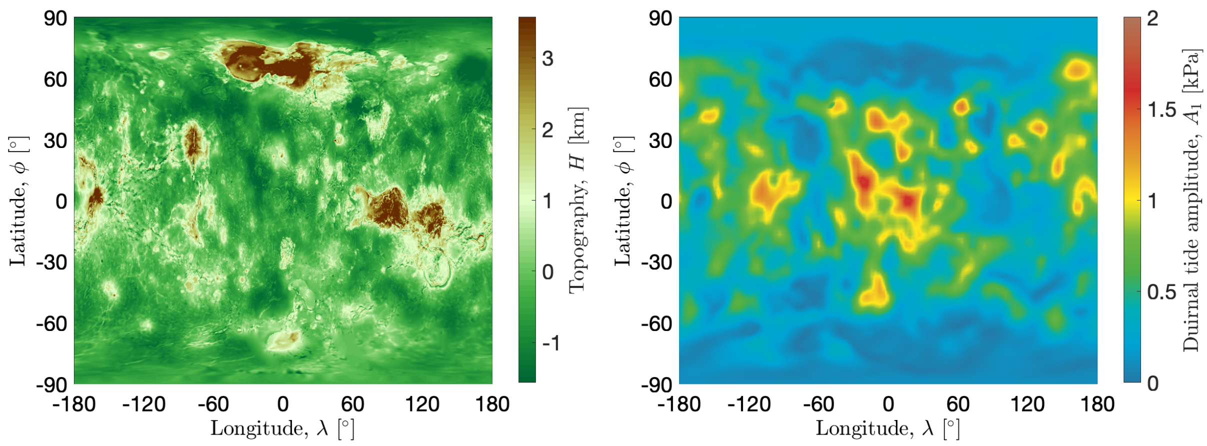

Figure 1: Left: Map of Venus' topography [22]; Right: Map of amplitude of the diurnal thermal tide