THE MANTLE VISCOSITY STRUCTURE OF VENUS J. S. Maia[1], M. A. Wieczorek[2], and A.-C. Plesa[3], [1]Observatoire de la Côte d'Azur, Laboratoire Lagrange, Université Côte d'Azur, Nice, France (julia.maia@oca.eu), [2]Institut de Physique du Globe de Paris, [3]Institute of Planetary Research, German Aerospace Center (DLR).

Introduction: It is broadly accepted that Venus is a geologically active world, presenting signs of recent volcanism and tectonism [e.g., 1,2]. Yet, its interior structure and dynamics are poorly understood. One of the most informative ways of investigating Venus's interior is to jointly analyze gravity and topography data. The initial gravity and topography studies of Venus that made use of the Pioneer Venus and later Magellan data revealed unique properties of the planet's interior. The gravity-topography correlations for long wavelengths are considerably higher than for Earth [3]. In addition, the global apparent depth of compensation is quite large, over 100 km [4]. Taking these characteristics into account, along with the observed wavelength dependent gravity-topography, the so-called spectral admittance, [4] concluded that the long-wavelength topography of the planet was supported through mantle flows, which is commonly referred to as dynamic or active support.

Several gravity and topography investigations of Venus were perform with the goal of better understanding its mantle properties. Many of these made use of the dynamic loading model developed by Hager and Clayton (1989) [5]. This model predicts the dynamic gravity and topography for a given density anomaly distribution in the mantle and a specified radial viscosity profile. Some studies [e.g., 6] focused on estimating the spatial distribution of density anomalies within the mantle, which supported the interpretation that volcanic rises are associated with mantle upwellings. Alternatively, other studies [4,7,8,9] were interested in investigating the planet's mantle viscosity structure.

We present a new investigation of the dynamic gravity and topography signatures on Venus making use of a multitaper spectral localization technique and a Bayesian inversion approach in order to provide new constraints to the mantle viscosity structure of our sister planet. The analysis is done with the VenusTopo719 topography model [10] and the MGNP180U gravity solution [11], both derived from the final Magellan mission datasets.

Methods: We adopt the dynamic loading model of [5], in which mantle flow is triggered by density anomalies in the mantle. The model solves the creeping flow equations for a Newtonian fluid assuming that the viscosity only varies with depth. With these simplifications the problem can be solved analytically using a radial propagator matrix technique. The solution is propagated from the core-mantle boundary (CMB) to the surface, passing through an arbitrary number of layers with different viscosities. For a given viscosity profile the model predicts the dynamic topography for each interface, as well as the associated gravity anomaly which is the sum of contributions from the dynamic topography and from the density anomalies. We note that these estimations are only sensitive to relative viscosity variations, so we are unable to estimate the absolute viscosity profile.

The gravity and topography signal predicted by the dynamic model can then be compared with the observations, allowing us to estimate the viscosity structure of the planet. In doing so, we assume that these observations are exclusively manifestations of mantle flow. However, there are major regions on Venus that are inconsistent with dynamic support, such as Ishtar Terra and the crustal plateaus [e.g., 12]. Hence, we adopt a localized spectral analysis [13] to suppress the signals from major shallowly compensated regions (Ishtar Terra, Ovda, and Thetis Regiones). In Figure 1 we present the observed spectral admittance and correlation for the entire planet and for the localized region of analysis. There is a clear increase in both the admittance and correlation when the data are localized, especially for long wavelengths. This is a result of excluding regions that have high elevations but that are close to isostatic compensation, and hence have low gravity signals. Applying the same localization procedure to the data and models, and considering only low degrees (≤ 32), we next investigate the 1D radial viscosity profile and the depth of loading in the mantle using a Bayesian inversion approach. For this, we make use of the DYNESTY package, which is a Python implementation of the dynamic nested sampling method [14].

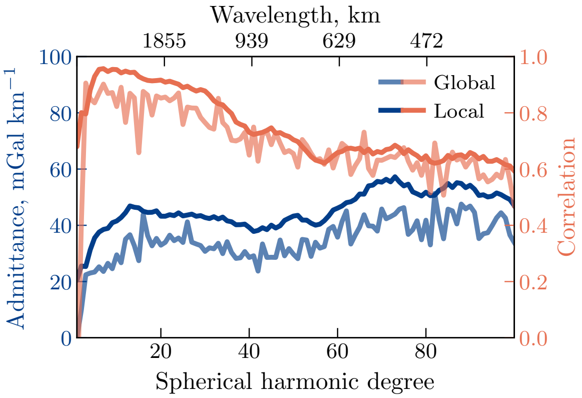

Figure 1: Global and localized spectral admittances (blue curves) and correlations (orange curves).

Results: We performed the inversion using a 4-layer viscosity model with free-slip boundary conditions at the CMB and no-slip boundary conditions at the surface. We defined a priori that the top layer must have a viscosity larger than the layer below it, representing the high-viscosity lithosphere, and the depths of all layers were allowed to vary freely. For simplicity, the mantle density anomalies were modeled as a single thin mass-sheet [6,8] whose depth was allowed to vary. Figure 2 shows the resulting mantle viscosity posterior distribution of the viscosity structure, in which the orange line represent the average viscosity for each depth. The gray rectangle indicates the accepted range for the mass-sheet depth, which is constrained between 200 and 280 km.

The inferred viscosity profiles show a distinct viscosity jump of about one order of magnitude located at depths ranging from 270 to 360 km which represents the presence of a low viscosity zone (LVZ) confined between the base of the lithosphere (thin and strong upper layer) and the underlying higher viscosity mantle. We found that the lower mantle is roughly isoviscous, although some models showed a low viscosity layer near the base of the mantle. The viscosity contrast between the lithosphere and the underlying mantle is poorly constrained but the depth of the interface is estimated to be less than 150 km with a median value of 75 km. This relatively thin lithosphere is coherent with elastic and mechanical thickness estimates found by flexural studies [e.g., 15]. Finally, we tested many other inversions, changing the boundary conditions, number of layers, and parametrizing the density anomalies uniformly with depth [4, 8] and the results were largely consistent, with similar depths and magntitudes for the LVZ in the upper mantle.

Discussion and conclusion: The most prominent finding of our analysis is a low viscosity zone below the lithosphere, with viscosity values of about one order of magnitude lower than the underlying mantle and with a thickness ranging from 150 to 300 km. This LVZ is consistent with an asthenosphere-like layer on Venus. The asthenosphere of Earth is a mechanically weak layer characterized by low seismic velocities [16] and low viscosities [e.g., 5, 17]. In oceanic regions the asthenosphere corresponds to a sharp seismic discontinuity at $\sim$70 km that extends downward to $\sim$400 km. For the continental upper mantle the asthenosphere-lithosphere boundary occurs at $\sim$200 km, but the seismological signature is much weaker. Moreover, several postglacial rebound and dynamic loading studies for the Earth indicate that the LVZ has viscosities 100–1000 times lower than the underlying mantle [17], although continental regions probably have less pronounced viscosity contrasts [18].

Most previous gravity studies for Venus inferred that the planet probably lacks a LVZ in the upper mantle [4,7,9]. However, these only tested a few representative models, mostly investigating the possibility of a LVZ that goes down to the upper-lower mantle interface, at a depth similar to the 660 km phase transition on Earth. Alternatively, [8] performed Monte Carlo inversions and found many models consistent with the presence of a LVZ with a thickness of a couple hundred of kilometers.

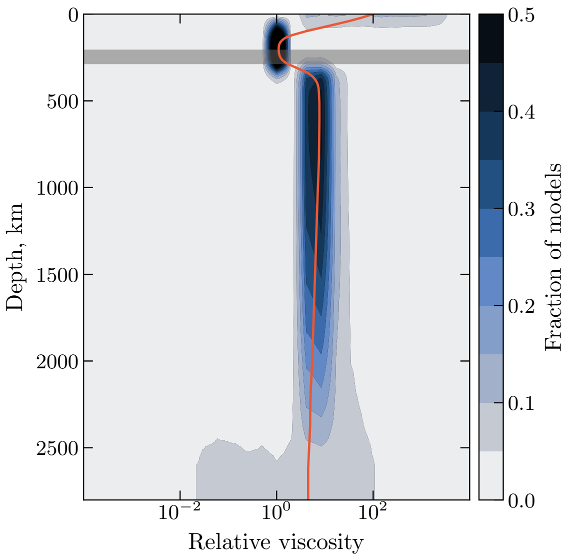

Figure 2: Posterior distribution of the mantle viscosity structure. The orange curve shows the average viscosity at each depth. The gray rectangle indicates the 1-σ range of estimated mass-sheet depths. All profiles are reference to the viscosity of the second layer.

Several physical processes could be responsible for the LVZ that we find, including partial melt and/or the presence of volatiles. For the Earth's asthenosphere many studies indicate that partial melting plays an important role and that this melt is most likely the source of mid-ocean rigde basalts [16]. Nevertheless, there are still discussions about the nature of this layer and the presence of water could also be relevant. Regarding Venus, the argument for a water-poor mantle has been used to explain the lack of plate tectonics, although there are virtually no constraints on the volatile content in the planet's interior. Alternatively, the prospect of partial melt in Venus's mantle is reasonable given the indications that the planet is volcanically active [e.g., 1].

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