MODELING AIRGLOW DISTURBANCES INDUCED BY QUAKES ON VENUS: PERSPECTIVES FOR FUTURE OBSERVATIONS. B. Kenda¹, P. Lognonné², A. Komjathy², B. Banerdt², J. Cutts², B. Sutin¹, A. Didion¹ and J. Jackson³, ¹Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR 7154 CNRS, Univ. Paris Diderot, 75013 Paris, France, ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91109 CA, ³California Institute of Technology, Pasadena 91125 CA.

Introduction: Despite its similarities to the Earth - mass, radius and distance to the Sun - Venus went through a very different evolution that led to present-day dissimilar conditions and dynamics. This process is not well understood and constrained, mainly because of the lack of information about Venus' internal structure and geological activity. Therefore, seismology appears to be well-suited to unveil many mysteries of the Earth's twin. However, the extreme surface conditions, including the very high surface temperature, prevent "classical" seismology using available technologies. For these reasons, we explore the novel opportunity of remote-sensing seismology in the atmosphere of Venus. Ionospheric and atmospheric seismology are well-established techniques in the case of the Earth and we investigate analogous effects on Venus with physics-based modeling in view of future exploration.

VAMOS: The Venus Airglow Measurements and Orbiter for Seismicity (VAMOS) investigates the opportunity of studying the seismicity and the interior structure of Venus by means of remote-sensing seismology, [1]. Indeed, the dense atmosphere which surrounds the planet is strongly coupled to the planet itself; thus, seismic waves, generated by quakes, will propagate as acoustic pressure waves in the atmosphere inducing strong signatures. In the case of the Earth, a variety of techniques allow routine detection by ground-based and satellite observations following quakes and tsunamis: e.g., fluctuations in the total electron content of the ionosphere, radio occultation and airglow imaging ([2,3]). On Venus, even if the seismic activity is anticipated to be weaker, the seismic coupling with the atmosphere is more efficient because of the higher density at the surface. Moreover, the brightest airglow in the solar system occurs on the nightside of Venus and can serve as a tracer to detect propagating seismic waves. We thus modeled what a single orbiting airglow camera would see after a quake (Fig. 1) and investigated the scientific implications of these observations. For the purposes of seismology, the main advantage of a camera with a large field of view is that each pixel acts as a seismometer: a single instrument can be used as a seismic network with almost a million stations.

Modeling: We produced synthetic signals of the expected fluctuation in the airglow emission on Venus induced by a quake in several steps.

Normal Modes of Venus. Normal-mode summation can be used to compute synthetic seismograms for planets with atmospheres, [4]. For Venus, we computed the fundamental Rayleigh modes and the first five overtones up to 50 mHz; the interior model for Venus is based on the Preliminary Earth Model since it is largely unknown, whereas for the atmosphere we used the General Reference Atmospheric Model and included viscous and molecular relaxation of CO₂. The analysis of the normal modes performed in [5] shows that on Venus a significant amount of the energy of the modes resides within the atmosphere. Moreover, the exponential decay of density with altitude induces an amplification effect and therefore the amplitude of the seismic signals in the atmosphere at higher altitude is found to be larger by orders of magnitude.

Fluctuations in the Airglow Emission. The nighttime emission at 1270 nm originates from the recombination of free oxygen atoms at altitudes between 90 and 120 km. Measurements from the VIRTIS camera onboard Venus Express resulted in maps and vertical profiles of the phenomenon, [6]. We used this data as the static background which is perturbed by seismic-coupled acoustic waves, as detailed in [5]. The fluctuation in the volumetric emission rate (VER) is described by the equation

$$\delta \text{VER} = -\frac{\tau}{1 + i\omega \tau} \text{div}(\text{VER} \cdot \nu)$$

where $\nu$ is the vertical velocity of the wave, $\tau$ the radiative lifetime and $\omega$ the angular frequency of the mode. The VER fluctuation is then integrated over the line of sight to reproduce the signal a camera would detect from outside the atmosphere.

Maps of quakes. The procedure described above can be repeated for each pixel in the field of view, leading to synthetic images of the wavefield. Fig. 1c shows an example for a Magnitude 6.5 quake, and the fluctuation is shown 33 minutes after the quake, when the disturbance is traversing the field of view of the camera. The anticipated noise level (Fig. 1b) is based on an existing camera design and observed Venus Express background (Fig. 1a). Modeling of the airglow signals are in progress, in order to integrate the various sources of noise and to optimize the camera design and reduce noise, particularly shot noise, due to the limited number of photons available for short exposures.
Fig 1: From left to right: (a) Background (non-global Venus Express observations from [6] have been modified to get full coverage; (b) Observed signal (in photons number) with shot noise and injected seismic signal; (c) Signals are computed on $25^2$ km$^2$ pixels for a 10 sec integration time with non-optimized design in term of shot noise.

Discussion and Perspectives: Physics-based modeling shows that large quakes on Venus could generate fluctuations in the airglow emission detectable by an orbiting camera. Not only is the signal larger than the expected noise, but it has distinctive characteristics which will allow us to distinguish it from other atmospheric disturbances. Indeed, frequency, wavelength and particularly horizontal velocity (around 4 km/s) are typical of seismic waves. Therefore a spectral analysis would clearly illuminate these seismically-induced fluctuations. Moreover, additional integration of the pixels will be made with respect to the epicentral distance and will decrease the detection threshold to a target in the magnitude range of 5-5.5.

If such signals were detected, it will be possible to determine the source characteristics and to explore the shallow interior structure of Venus. Indeed, the epicenter can be immediately located as the geometric center of the circular wavefield on a single frame, and the magnitude can be estimated from the amplitude. For the structure, the dispersion of the surface waves, i.e. the frequency-dependence of their velocity, allows us to explore the crustal and lithospheric structure. As an example, we considered the time-series at two pixels with different epicentral distances (Fig. 2a). By cross-correlation, in different frequency bands (Fig. 2b), the dispersion curve can be retrieved and compares well with the theoretical prediction (Fig. 2c); in this curve, the location of the knee defines the thickness of the Venus crust. A more complete analysis should improve these results and actual observations could lead to a structural inversion in terms of seismic velocities and physical properties with depth. In addition, with sufficiently large seismic events, the potential exists for identifying lateral variations in crustal thickness.

These results are promising for possible future discoveries on Venus through atmospheric and remote-sensing seismology, as developed by the VAMOS concept.

Fig 2. Rayleigh-wave dispersion from airglow synthetics. a. Two airglow-grams at different epicentral distances. b. The cross-correlation of the two signals gives the delay in time, resulting in the propagation velocity. c. Reconstructed and theoretical dispersion curve for the Rayleigh fundamental mode.