

**INSIGHTS ABOUT RELATIONS BETWEEN VENUSIAN VOLCANIC ACTIVITY AND ORBITAL MOVEMENT.** L. S. Villanova<sup>1</sup>, <sup>1</sup>Department of Earth and Planetary Science, The University of Tokyo, villanova@eps.s.u-tokyo.ac.jp.

**Introduction:** The potential seismicity of Venus has been discussed over recent decades. Even though Venusian seismic recordings are not available, measurements of sulfur dioxide (SO<sub>2</sub>) were made from sensors of the Pioneer Venus (1978-1979) and Venus Express (2006-2014) missions [1] and were related to volcanic activity. Measurements of SO<sub>2</sub> in the Venusian atmosphere have been related to volcanic activity [2], which is partially related to seismicity and may give some information about the heat flow on the mantle. On Venus, seismicity at volcanoes has been correlated with the gravitational tide and thermal tide by solar heating.

Small amounts of sulfur dioxide from the deep mantle are brought to the surface by volcanism. They are ejected by eruptions into the atmosphere in form of dust. These eruptions could explain changes in SO<sub>2</sub> values seen by the Pioneer Venus UV spectrometer, in the atmosphere at 70 km high [3]. The thermal evolution of a magma ocean is closely related to the formation of a steam atmosphere. A massive atmosphere decreases outgoing radiation from the planet through greenhouse effects and delays the solidification process [4]. Thus, planetary radiation would be a restraining factor in the heat flux from the deep magma ocean [4]. Finally, a magma ocean is effective transportation of internal heat to the surface.

Studies about the gravity field suggested that Venus does not present a shallow asthenosphere like Earth [5]. The convection in the terrestrial asthenosphere is the principal control of thermal and geological evolution. On the other hand, if Venus' asthenosphere is deeper, then the heat flow in the deep mantle may be directly reflected on the surface [5,6]. Since the lithosphere is not moving, the volcanic and tectonic features of the mantle plumes are concentrated. As the plumes intrude the lithosphere, they will flatten and create a dome in the crust. The uplift may crack the crust and form fractures/rifts [5,7], presenting seismic activity.

On Earth, seismicity at volcanoes and its features have been correlated with tidal effects (e.g., [8]) on a large amount of magma. However, a so obvious correlation does not appear on Venus, despite the extensive presence of magma [9]. The explanation may be related to the Venus rotation, due to gravitational tide and thermal tide in the atmosphere by the differential heating of the Sun [10].

**Methods:** To analyze relations between the SO<sub>2</sub> measurements on Venus and orbital parameters, time series were produced with month values and joined in a single dataset. SO<sub>2</sub> measurements of the Venus Express (2006-2014) mission was chosen to produce the time series, since this is the more recent and long dataset, with no gaps. Orbital parameters of the Venus-Sun system were calculated using NASA's HORIZONS interface.

The time series of Venusian SO<sub>2</sub> was analyzed by wavelet transform to detect periodicities and frequencies contained in the signal. All series were analyzed by machine learning methods, to detect which orbital relationships may influence the Venusian SO<sub>2</sub> variations/emissions. Results are presented in the percentage of relations between the parameters is a two-dimensional array of associated merit scores as doubles.

**Results/discussion:** The wavelet transform analysis was performed to identify cyclicity and frequencies in the SO<sub>2</sub> time series. Peaks with the highest values of SO<sub>2</sub> measurements per month are concentrated mostly in 2009 and 2010 (Figure 1b). Looking at the wavelets, it is possible to observe that frequencies of the Venusian SO<sub>2</sub> are majority concentrated on periods of ~4 (0.3 yr.) and ~7.5 (0.6 yr.) months (Figure 1a).

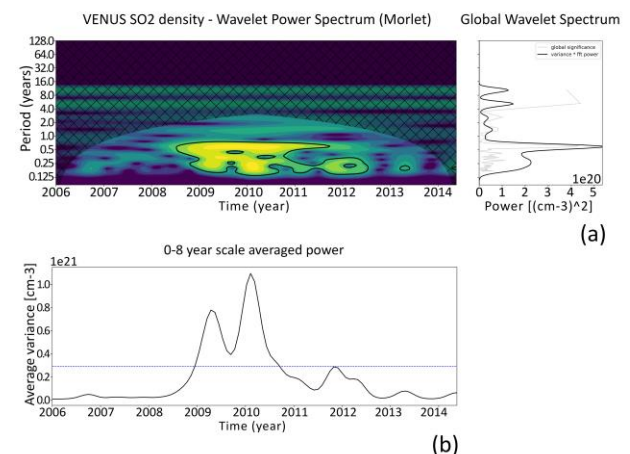


Figure 1 - Venusian SO<sub>2</sub> time series spectral analysis. (a) Wavelet transform and wavelet spectrum and (b) the 8 years scale-averaged power.

Machine learning analysis was performed to infer correlations among orbital parameters and the deep seismicity/volcanic activity. The percentage of correlation between the time series is shown in Table 1. Error of 4%.

Table 1 – Correlation between the time series

Orbital parameters	Correlation (in %) with the time series of VENUS: SO <sub>2</sub> density per month (cm <sup>-3</sup> )
Eccentricity, e (EC)	100
Periapsis distance, km (QR)	-
Inclination of plane, degrees (IN)	-
Longitude of Ascending Node, degrees (OM)	-
Argument of Perifocus, degrees (W)	100
Time of periapsis relative to epoch, s (Tp)	90
Mean motion, degrees/s (N)	-
Mean anomaly, degrees (MA)	20
True anomaly, degrees (TA)	-
Semi-major axis, km (A)	-
Apoapsis distance, km (AD)	-
Sidereal orbit period, s (PR)	-

Venus completes its orbit every 224.65 days (about 7.5 terrestrial months). When Venus comes between the Earth and the Sun every ~584 days, a position called inferior conjunction has the closest approach to Earth of all the planets. The Venusian orbit is slightly inclined with respect to the Earth's orbit, thus every 19 months, Venus passes between the Earth and the Sun. The period of orbit of Venus brings interaction between the Sun's gravitational tide and an atmospheric tide created by solar heating in the atmosphere. This may explain the energy concentration in the wavelet (Figure 1), in the period of ~7.5 months (0.6 yr.) and its division in ~4 (0.3 yr.), related to extreme points in the quadrants of the orbit.

A tidal effect is produced when the gravitational attraction of a body is appreciably greater at the nearest part of a second body than at its center. Tidal action derived from orbital movement in the planetary interior spurs volcanism. Internal heating dominates the energetics of the flow and produces large-scale upwelling. Heating at the base of the mantle produces upwelling mantle plumes.

Analyzing the results of Table 1, the orbital parameters EC and W of Venus presented the highest correlation in common with the series of Venusian SO<sub>2</sub> values. The EC parameter allows conjunctions to occur

since the Venusian eccentricity is nearly circular. The parameter W concerns the distance from the periapsis to the ascending node, in relation to the orbital plane around the Sun, related to the 'dance' between the Venus-Earth-Sun system, considering that solar tides are more influential.

Values of SO<sub>2</sub> emissions showing more correlation to the EC and W parameter may be related to perturbations that make each body move in its orbit, influencing the internal dynamics. As Venus' lithosphere has no movement derived from tectonic plates, the flow in the deep mantle may be reflected in the surface, being the main mechanism of internal heat flow, and consequently to volcanic activity.

The synodic periods of Venus are almost equal to 8 terrestrial years (about the same duration as the period of the terrestrial parameter W). This small difference causes Earth to lag behind Venus ~2.5 days each five conjunctions [11]. This is enough to move Venus in its orbit against the ecliptic (EC), causing more perturbations than the inclination of the plane, opposing what happens on the Earth. This situation is the result of a slow drift to the west of the inferior conjunction point around the Sun [11].

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**References:** [1] Marcq et al. (2013). *Nat. Geosci.*, **6**, doi.org/10.1038/ngeo1650. [2] Krishnamoorthy et al. (2021). *White Paper NASA 2021 Decadal Survey*, SAND2020-2849R. [3] Truong & Lunine (2021). *Proceedings of the National Academy of Sciences*, **118:e2021689118**. doi.org/10.1073/pnas.2021689118. [4] Hamano et al. (2013). *Nature*, **497**, doi.org/10.1038/nature12163. [5] Phillips & Hansen (1998). *Sci.*, **279**, doi.org/10.1126/science.279.5356.1492. [6] Suetsugu et al. (2005). *Encyclopedia of Geology*, **335-343**, doi:10.1016/B0-12-369396-9/00131-3. [7] McNutt & Caress (2007). *Treatise on Geophysics*, **445-478**, doi.org/10.1016/B978-044452748-6.00013-4. [8] Rydelek et al. (1988). *J. Geophys. Res.*, **93(B5)**, doi.org/10.1029/JB093iB05p04401. [9] Tolstoy et al. (2002). *Geology*, **30(6)**, doi.org/10.1130/0091-7613. [10] Takagi & Matsuda (2007). *J. Geophys. Res.*, **112:D09112**, doi.org/10.1029/2006JD007901. [11] Maor (2004). *Princeton University Press*, ISBN 13: 9780691115894.