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[1] The possibility to detect seismic activity on Venus by using the mechanical coupling of the solid-atmosphere system is investigated. First, the atmospheric attenuation of infrasonic waves produced by quakes is theoretically determined from a pure CO_2 atmospheric model, demonstrating that frequencies below 0.1 Hz are amplified by a factor of 10 000 above 120 km altitude. With a simple quake model, an upper limit of infrasonic adiabatic temperature and density perturbations above the source is estimated. Then, we demonstrate that the temperature increase due to high altitude acoustic energy dissipation above a quake is large enough to be measured by remote sensing methods. Finally, the expected post-seismic effects are analyzed in the framework of the VIRTIS instrument on board the ESA Venus Express mission. **Citation:** Garcia, R., P. Lognonné, and X. Bonnin (2005), Detecting atmospheric perturbations produced by Venus quakes, *Geophys. Res. Lett.*, *32*, L16205, doi:10.1029/2005GL023558.

1. Introduction

[2] The Earth interior is known to be seismically coupled with the atmosphere [*Lognonné et al.*, 1998]. Seismic Rayleigh waves are excited by various atmospheric infrasound sources, either explosive volcano eruptions [*Widmer and Zürn*, 1992; *Kanamori and Mori*, 1992] or atmospheric turbulences [*Suda et al.*, 1998; *Kobayashi and Nishida*, 1998; *Tanimoto et al.*, 1998]. In an opposite way, acoustic waves generated by the Rayleigh surface waves have been observed in the far field of very large ($M_s > 7$) quakes [*Ducic et al.*, 2003; *Artru et al.*, 2004] but also in the near-field of smaller quakes. *Calais and Minster* [1995] reported ionospheric perturbations in GPS data following the Northridge $M_w = 6.7$ earthquake, and observations have been done for magnitude as low as 5.9, with reported thermospheric perturbations of about 300 K between 300 and 400 km of altitude [*Kelley et al.*, 1985]. We study in this paper the amplitude of such near field signals on other planets than the Earth and the possibility to use these perturbations as indicator of the seismic activity of a planet.

[3] Compared to Earth, Venus is the only terrestrial planet where the probably weaker seismic activity is counterbalanced by a better atmospheric coupling. This coupling is proportional to the acoustic impedance of the atmosphere. Due to a larger atmospheric density at the surface (60 kg/m^3), the acoustic impedance is about 60 times greater than on Earth. Moreover, because of the low attenuation in the lower atmosphere, the velocity amplitude of the waves increases as $\sqrt{\frac{\rho(0)}{\rho(z)}}$ where $\rho(z)$ is the density at an altitude of z. The almost 2 orders of magnitude density decrease in the first 50 km leads to a wave amplification by 10. As the Venusian pressure at 50 km of altitude is comparable to the Earth's one at the ground, for the same quake magnitude, infrasounds in Venus will have amplitudes about 600 times larger than those recorded on Earth at the same pressure level.

[4] We explore in this paper the possibility to observe with such amplification, moderate magnitude quakes in the Venus atmosphere. We consider only waves with frequencies larger than both the Brunt-Väisälä frequency (≈1.7 mHz), and the atmospheric acoustic cutoff frequency (≈4.8 mHz). These waves are therefore acoustic waves which are propagating nearly vertically above the quake.

[5] In a first part, the attenuation of infrasonic waves in the atmosphere of Venus is investigated. Then, the acoustic signals and their dissipation above a fault rupture are estimated. This allows us to determine the temperature and density perturbations generated in the upper atmosphere of Venus. Finally, an observation strategy is presented for detecting post-seismic atmospheric perturbations with the VIRTIS instrument on board the Venus Express ESA mission.

2. Infrasound Atmospheric Signals and Venus Atmospheric Model

[6] Due to the high surface temperature, the thickness of the seismogenic layer on Venus is probably not larger than 30 km, due to the smaller depth of the brittle/ductile crustal transition in the crust. Mainly shallow quakes are therefore expected. Almost half of the energy of these quakes will be radiated toward the surface, leading to acoustic signals, propagating mainly along the vertical direction, due to the large acoustic velocity variation between the interior and the atmosphere. These acoustic signals will produce temperature oscillations, due to the adiabatic pressure variations of the waves, but also an atmospheric temperature increase, due to the deposition of the acoustic energy associated to nonadiabatic processes. The flux of mean kinetic energy in the tube of an acoustic ray is a constant value in a perfect, non conductive, fluid. For the altitudes where attenuation can be neglected, the decrease of density, and therefore of the thermal inertia of the atmosphere, produces increasing adiabatic temperature oscillations with altitude. However in a real fluid, acoustic waves encounter at high altitude attenuation due to viscosity, thermal conduction and molecular vibrational and rotational relaxations [*Bass et al.*, 1984]. A second temperature signal might therefore be

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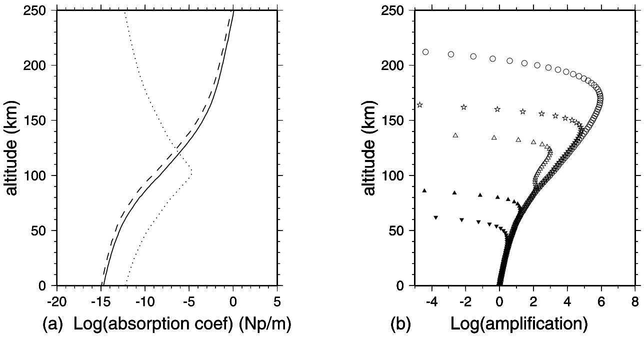

Figure 1. (a) Logarithm of classical (full line), rotational (dashed line) and vibrational (dotted line) absorption coefficients as a function of altitude (in km) in the atmosphere of Venus at 0.1 Hz. (b) Logarithm of the acoustic wave amplification factor as a function of altitude (in km) in the atmosphere of Venus assuming a vertical propagation of acoustic waves. Plots are given for different frequencies: 10 mHz (open circles), 100 mHz (open stars), 1 Hz (open triangles), 10 Hz (filled triangles) and 100 Hz (filled inverted triangles).

observed through an upper atmosphere warming due to the deposition of acoustic energy.

[7] In order to estimate the range of altitude for these two regimes, we have computed the acoustic attenuation in the atmosphere of Venus, assuming an atmosphere with pure CO_2 and following the study of *Bass and Chambers* [2001]. The atmospheric physical parameters [*Hunten et al.*, 1983], in combination with CO_2 properties extracted from CO2TAB software and the *Bass and Chambers* [2001] study, are then used for computing all the parameters relevant to the atmospheric acoustic attenuation.

[8] Three different types of sound absorption are observed: the classical absorption (α_{cl}) due to viscosity and thermal conductivity effects, and the rotational (α_{rot}) and vibrational (α_{vib}) relaxation absorptions due to the rotational and vibrational modes of CO_2 molecules respectively [*Bass et al.*, 1984]. These three coefficients depend on the acoustic wave frequency, on the pressure and on the temperature. See *Bass and Chambers* [2001] for a full description of these three absorption coefficients. The parameters used in the computation of the rotational and vibrational absorption have been validated by experiments only for frequencies above 10 Hz [*Bass et al.*, 1984]. However, as shown below, the classical attenuation is dominating for frequencies below 1 Hz where most of the seismic energy is generated for the quake magnitudes considered, validating our analysis. Figure 1a shows these absorption coefficients with altitude for a 0.1 Hz acoustic wave. For this frequency, the vibration absorption shows a resonance at 100 km height, but the value of this absorption coefficient is low.

[9] The amplification factor of vertically propagating acoustic waves are plotted in Figure 1b for different wave frequencies. With our hypotheses, the amplitude of acoustic waves increases proportionally to the inverse square root of density and then decreases due to attenuation. In the acoustic frequency range (above 10 Hz) the waves do not reach altitudes greater than 80 km due to the vibrational absorption effects. This result has already been underlined for the atmosphere of Mars, where temperature, pressure and molecular compositions are similar to the Venusian one at 80 km altitude [*Bass and Chambers*, 2001]. However, in the infrasonic-seismic frequency range (5 mHz–1 Hz), the classical absorption is dominant, and the waves reach altitudes higher than 100 km with amplification factors greater than 10^4. This result suggests that, at low frequencies (i.e. below 0.1 Hz), the waves produced by quakes and volcanic eruptions are strongly amplified in the upper atmosphere of Venus (above 100 km altitude). Can they be detected through their temperature perturbations? For which magnitude threshold can we envisage the detection of these effects?

3. Acoustic Signals and Adiabatic Perturbations

[10] In order to estimate these temperature signals, which depend on the spectrum of the generated acoustic waves, the source of Venus quakes is modeled with a simple Haskell model [*Aki and Richards*, 1980] for the rupture on a reverse fault at the limit of the seismogenic layer (30 km depth). Venus is a tectonically active planet as demonstrated by the young age of its surface. Prediction suggests that 100 quakes of surface wave magnitude greater than 5 could be released by an intraplate activity with a strain rate of $10^{-19}s^{-1}$ [*Stofan et al.*, 1993]. In particular, *Solomon et al.* [1999] and *Dragoni and Piombo* [2003] have suggested that wrinkle ridges in volcanic plains are associated to compressive stresses in the crust due to the atmospheric temperature variations produced by the release of greenhouse effect during the last global volcanic activity. Such mechanism might produce reverse faults and could lead to quakes of maximum magnitude 6.5.

[11] We compute the seismic wave field radiated in an homogeneous half space, with parameters extracted from AK135 Earth's seismic model at 30 km depth [*Kennett et al.*, 1995]. Transmission coefficients at the interface between the crust and the atmosphere of Venus give the displacement at the base of the atmosphere [*Cerveny*, 2001]. Figure 2 plots the time integrated azimuthal average of acoustic energy density at the base of the atmosphere as a

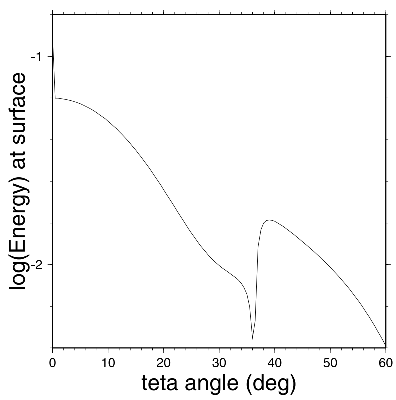

Figure 2. Time integrated azimuthal average of acoustic energy density radiated at the surface (in J.s/m^3) as a function of the angle teta (in degree) between the epicenter, the hypocenter and the surface point. Computations are performed for a magnitude 6.0 quake.

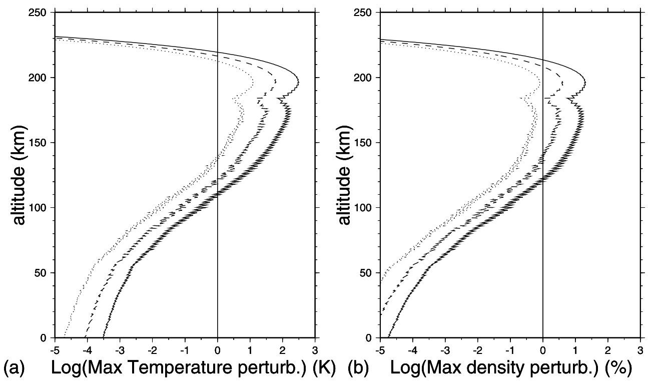

Figure 3. Logarithm of (a) the maximum adiabatic temperature perturbation (in K) and (b) the maximum density perturbation (in %), just above the source, as a function of altitude (in km) for different earthquake magnitudes: M5.0 (dotted line), M5.5 (dashed line) and M6.0 (plain line). Vertical bars are visual guides at 1K and 1% levels.

function of the angle between the epicenter, the hypocenter and the surface point. This figure demonstrates that the main part of the energy radiated in the atmosphere is concentrated in a cone of 60 degrees aperture from the earthquake hypocenter. With an event's depth of 30 km, the surface area radiating the main part of the energy has a radius of 52 km around the epicenter. Due to incidence angles lower than 6 degrees above the radiating surface area for altitudes lower than 200 km, we use a vertically propagating plane wave approximation for the infrasonic wave in the atmosphere. We are also neglecting atmospheric winds: the propagation time of the acoustic signal until 200 km height is indeed about 730 seconds and the high winds observed in the Venus atmosphere ($\approx$100 m/s) [*Donahue and Russel*, 1997; *Lellouch et al.*, 1997] will shift the signals by about 70 km at 200 km height.

[12] We have first computed the adiabatic temperature and density perturbations produced by the infrasonic waves. Figure 3 is presenting the maximum adiabatic temperature and density perturbations produced just above the quake as a function of altitude for different magnitudes. Such a computation is an upper limit for the adiabatic perturbations, but it demonstrates that low frequency infrasonic waves (below 0.1 Hz) could produce large temperature and density perturbations at high altitudes (above 120 km).

4. Nonadiabatic Attenuation and Seismic Plumes

[13] We therefore focus now on the energy deposited by nonadiabatic effects, which leads after the quake, to thermal anomalies subsequently diffused by the atmospheric heat conduction. The vertical profile of dissipated acoustic energy is computed by using the absorption coefficients obtained in the second section, averaged over the radiating surface area, and time integrated over the length of the acoustic signal. Below 170 km altitude, the characteristic time for a thermal conduction over 50 km is much larger than the maximum period ($\approx$200 seconds) of the acoustic signals produced by the quake. So, the energy dissipation and the consequent temperature increase, could be considered as instantaneous relative to the thermal conduction time. Above 170 km height, the temperature perturbation will diffuse rapidly. The energy dissipation is converted to temperature variations by using the calorific capacity of the atmosphere. The subsequent temperature perturbations of the atmosphere as a function of altitude are presented in Figure 4 for different quake magnitudes. The temperature perturbation is significant only at high altitudes, between 120 km and 170 km, where the dissipation of low frequency infrasonic waves is large. The temperature perturbation increases with magnitude due to an overall increase of the energy input, but also because the large magnitude events are producing more energy at low frequencies. This figure demonstrates that Venus quakes of magnitude 6.0 are producing temperature perturbations larger than 10K that could probably be detected by remote sensing methods. However, if we keep in mind that these temperature perturbations are averaged over a 50 km radius area, the Venus quakes of magnitude 5.5 will probably produce temperature perturbations larger than 1K on smaller areas just above the epicenter. Moreover, the previous analysis is only taking into account the first impulse of seismic energy. More energy will propagate upward in the same time window due to both the crustal reflections of seismic waves and the surface waves, decreasing the detection threshold.

5. Observation Strategy With VIRTIS Onboard Venus Express

[14] The VIRTIS instrument onboard ESA Venus Express mission is a visible and infrared thermal imaging spectrometer [*Drossart et al.*, 2004]. Its particularity is a mapping channel (VIRTIS-M), measuring one spectra per pixel on a line of 250 pixels, every 2.5 seconds, with a lowest surface resolution of 17 $\times$ 17 km^2 at apocenter. This instrument will measure absorption and emission lines of various components of the atmosphere of Venus, at different altitudes. In particular, non local thermodynamic equilibrium emissions of CO and CO_2, and O_2 nightglow

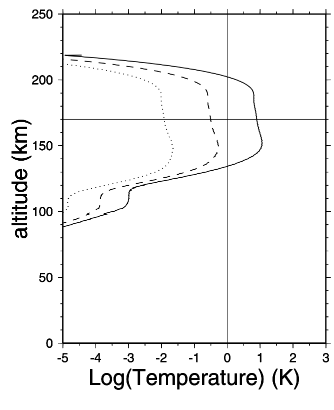

Figure 4. Logarithm of the local temperature perturbation (in K) averaged over a source area of 50 km radius, as a function of altitude (in km) for different earthquake magnitudes: M5.0 (dotted line), M5.5 (dashed line) and M6.0 (plain line). Vertical bar represents a detection threshold at 1K level, and horizontal line represents the maximum altitude at which the temperature increase could be maintained longer than 200 seconds.

are sensitive to temperature and density variations in the upper atmosphere [*Lellouch et al.*, 1997; *Roldán et al.*, 2000]. In order to detect the post-seismic temperature perturbations, all expected post-seimic effects must be analyzed relative to the available observation modes.

[15] The local temperature increase between 120 km and 170 km above the quake will concern a large surface, and will diffuse on time scales larger than 200 seconds. With a spatial resolution lower than 17 km and a time acquisition of 640s, the mosaic mapping mode of the VIRTIS-M HR sensor at the apocenter will be a good candidate for searching these signals.

[16] The adiabatic perturbations can be retrieved from VIRTIS-M HR in nadir line measurements, along the track, for spacecraft altitudes greater than 12 000 km: the ground track of the spacecraft is indeed moving at velocities smaller than 2 km/s ensuring an overlapping of successive pixels between two line images. So, the temperature and density variations in one radial profile can be followed during more than 2000 seconds for spacecraft positions close to the apocenter. Such performances might also allow a spectral analysis of the high altitude emissions created by adiabatic perturbations in order to search for atmospheric normal modes.

6. Conclusion

[17] The computations performed demonstrate that temperature perturbations due to the dissipation of the acoustic energy emitted by Venus quakes have amplitudes large enough to be measured with remote sensing instruments. The maximum adiabatic temperature and density perturbations produced by the infrasonic waves just above the earthquake give an upper limit for such effects and demonstrate that low frequency infrasonic waves produced by seismic waves can generate high temperature perturbations at altitudes above 120 km. Despite an overall simplification of the physical problem and limitations related to atmospheric winds, these estimates give the order of magnitude of the expected temperature perturbations. Future investigations must take into account the solid-atmosphere coupling through a normal mode analysis, the effects of winds, and the interaction between the infrasonic wave and the ionospheric plasma if radar techniques are considered for some future missions. From this study, an observation strategy is deduced for using VIRTIS instrument onboard Venus Express mission that will allow the definition of observation modes and data processing methods. The detection of Venus quakes and the determination of their magnitude and localization in time and space will strongly constrain the tectonic of Venus and allow correlations with other atmospheric data.

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