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Atmospheric excitation of planetary free oscillations

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Abstract. Seismology is a powerful tool for probing planetary interiors, and provides us with information on planetary evolution and material properties under high pressure and high temperature. However, seismology has been considered inapplicable to tectonically inactive planets. We, however, show that the atmospheres of solid planets are capable of exerting dynamic pressure on their surfaces, thereby exciting free oscillations with amplitudes that are large enough to be detected by broad-band seismographs. An order-of-magnitude estimate gives amplitudes of a few nanogals for the Earth, Venus and Mars despite the widely varying ambient conditions. The amplitudes are predicted to have weak frequency dependence. Continuous excitations of the Earth's free oscillations having the features predicted by our above theory have recently been confirmed by observations. Seismology promises to provide us with the internal structure of Venus and Mars.

Seismology is a powerful tool for probing planetary interiors [1], and provides us with information on planetary evolution and material properties under high pressure and high temperature. However, seismology has been considered inapplicable to tectonically inactive planets. The Sun pulsates due to acoustic waves generated by intensive turbulent gaseous motion on the top of the convective layer [5]. Similar processes should occur on solid planets having atmospheres, and should excite seismic waves that propagate throughout the solid interior, thereby inducing free oscillations. Such planetary atmospheric disturbances should occur even on tectonically inactive solid planets such as Mars and Venus.

We now estimate the order of magnitude of the seismic free oscillations excited by atmospheric disturbances following Kobayashi and Nishida [4]. In addition to using the theory from [4], we treat the Earth's atmosphere as a moist one in this article. Some atmospheric gases such as water vapour and carbon dioxide cause a so-called greenhouse effect [6]. Atmospheres are relatively transparent to visible light but have strong absorption at infrared wavelengths [7]. Visible light absorbed at and near the surface is converted and re-radiated at infrared wavelengths. The infrared rays are absorbed into the atmosphere and warm the air near the surface. The resultant buoyant force induces atmospheric convective motions. In a steady state, the heat flux transported by the atmosphere must be balanced by the net solar influx:

$$\frac{v^2}{H} = g\alpha\,\Delta T \tag{1}$$

$$S(1-A)/4 = (\rho_{\mathrm{at}} c_p \Delta T + \Delta h_{\mathrm{m}})v \tag{2}$$

where S is solar energy flux, A the albedo, ρ_{at} the density of the atmosphere at the surface, T the surface temperature, g the surface gravity, H the pressure scale height, c_p the specific heat at constant pressure, v the velocity and Δh_m the latent heat carried by the water vapour. We neglect the buoyancy force due to the variation in partial pressure of the water vapour because it is less by one order of magnitude than that due to thermal expansion. Δh_m is approximately the heat of vaporization multiplied by the increment in the number density of the water vapour due to ΔT. Using appropriate properties of water vapour at 285 K, dh_m/dT is found to be about 1.5×10^3 J K^{-1} m^{-3}, which is larger than $\rho_{at} c_p$ on the Earth. Since other planetary atmospheres are dry, the moisture effect is included only for the Earth's atmosphere.

From the above equations, the amplitude of the velocity fluctuation is

$$v = \left(\frac{g\alpha S(1-A)H}{4(\rho_{at} c_p + dh_m/dT)} \right)^{1/3}. \tag{3}$$

The associated dynamic pressure fluctuation is scaled as $p_0 = \rho_{at} v^2$, and the pressure disturbances, with the timescale $1/f$ (f is the frequency), are

$$\delta p = p_0 \frac{f_0}{f} \tag{4}$$

where $1/f_0 = H/v$ is the timescale of convective motion. This frequency dependence is obtained from dimensional considerations. To construct the dimension of the pressure in terms of S, H and the time $1/f$, we require S/Hf, to which the right-hand side of equation (4) is proportional. Although equation (4) was constructed by dimensional analysis, it is consistent with observations of atmospheric pressure. Here only temporal variations of convective cellular motions whose scale is about H are considered. Smaller-scale turbulence may be important for generation of acoustic waves in the atmosphere but is less effective in generating elastic waves in the solid portion of the planet.

Table 1. Physical parameters and excited amplitudes. S is the solar energy flux, A the albedo, ρ_{at} the density of the atmosphere at the surface, T the surface temperature, R the radius of the planet, g the surface gravity, H the pressure scale height, c_p the specific heat at constant pressure, v and p_0 scales of velocity and pressure fluctuations respectively and $\tau_0 = 1/f_0$ the timescale of the convective motions in the atmosphere.

Planet	S (W m^{-2})	A	ρ_{at} (kg m^{-3})[a]	T (K)	R (10^6 m)	g (m s^{-2})
Venus	2620	0.78	65.3	750	6.03	8.9
Earth	1370	0.30	1.16	290	6.38	9.8
Mars	590	0.16	1.33×10^{-2}	240	3.40	3.7
	H (10^4 m)	c_p (J K^{-1} kg^{-1})	v (m s^{-1})	p_0 (Pa)	τ_0 (10^3 s)	a (ngal)[b]
Venus	1.58	657	0.9	48	18	2.2
Earth	0.87	1030	2.0	4.8	2.2	0.9[c]
Mars	1.21	657	13	2.6	0.88	3.3

[a] We treat atmospheres as diatomic ideal gases. The molecular weights are 44, 28 and 44 for Venus, the Earth and Mars respectively.

[b] We used the solid density $\rho_{sol} = 4 \times 10^3$ kg m^{-3}, the surface wave velocity $c = 5 \times 10^3$ m s^{-1} and the quality factor $Q = 200$ to evaluate the resultant amplitudes. These values are typical for fundamental spheroidal modes in the mHz band. We also used these values for Venus and Mars.

[c] On the Earth, the energy is carried not only by sensible heat but also by the latent heat of water vapour. The effect is included.

Fluctuations of the pressure loading on the surface of the solid portion will preferentially excite fundamental spheroidal modes, because their elastic energy is confined to shallower depths than overtone modes. Here we use a simplified form of the comprehensive theory of excitation of free oscillations [8] to assess the excited amplitudes of the fundamental spheroidal modes. Let us consider a steady state in which a balance is achieved between the energy input from the atmosphere to a mode (with energy input rate G) and the dissipation of its elastic energy E (at the dissipation rate ΓE) in the same manner as in helioseismology [9]:

$$G = \Gamma E = \frac{\omega}{Q} E. \tag{5}$$

$E \approx \omega^2 M_e d^2/2$, where d is the displacement, ω is the angular frequency and M_e is the effective elastic mass ($\approx 4\pi R^2 \lambda \rho_{\rm sol}$ where R is the radius of the solid part of the planet). The input power is $G = \omega d F$, where the force exerted on a mode is $F = 4\pi R^2\, \delta p / L$. The cut-off angular order is $L = 2\pi R/H$. We assume that the horizontal correlation length of the random atmospheric disturbance is approximately equal to H, and the spatial power of the disturbance is equipartitioned into L^2 modes. From the above equations, we obtain the amplitude of the excited acceleration

$$a = \omega^2 d = \frac{Q H p_0 f_0}{\pi R \rho_{\rm sol} \lambda f} = \frac{Q H p_0 f_0}{\pi R \rho_{\rm sol} c} \tag{6}$$

where we use the horizontal wavelength $\lambda = c/f$ as the penetration depth. The frequency dependence of this amplitude is weak, since the quality factor Q and the surface wave phase velocity c are not strongly dependent on frequency in the mHz band. Using typical values for various parameters, we fortuitously obtain amplitudes of nanogal (10^{-11} m s^{-2})

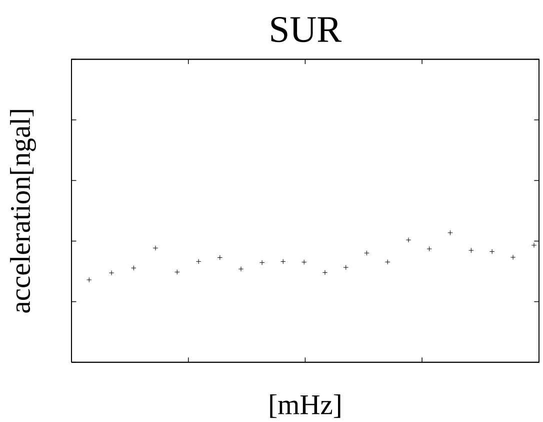

Figure 1. Amplitudes of continuously excited free oscillations of the Earth. The acceleration amplitudes for the fundamental spheroidal modes ${}_0S_{22}$–${}_0S_{43}$ are plotted at their frequencies [1]. To produce this figure, we excluded the effects of earthquakes with $M_0 > 10^{17}$ N m from the seismogram obtained at SUR (Southerland, Republic of South Africa) in 1992–1993: the continuous record is divided into segments about half a day in length with overlaps of about a quarter of a day. For each segment, we calculated the power spectral density (PSD) and discarded it if the PSD was affected by earthquakes. The average of the selected PSDs shows distinct peaks at the frequencies of the fundamental spheroidal modes. To exclude the background noise, the averaged PSD was fitted by signal profiles ($\sum_l s_l(f)$) and a background noise profile ($n_0 + n_1 f + n_\alpha f^\alpha$ where $\alpha \approx -3$). The amplitudes in the figure are calculated from the resultant signal profiles. Almost the same results are obtained from 13 other stations around the World. More details are given by Nishida and Kobayashi [11].

order for the Earth, Venus and Mars (table 1) in spite of the greatly differing solar energy input rates, planetary masses and atmospheric densities. Such amplitudes are detectable by standard broad-band seismographs [10].

Recently, continuously excited signals with frequency-independent amplitudes at the nanogal level have been reported in other studies [2–4]. For each mode, the amplitude at the nanogal level can be maintained by an energy supply of just 30 W! The amplitudes of these signals are very small, but are much larger than the steady-state amplitudes excited by earthquakes [3, 4]. In figure 1, a signal observed at the quietest station is shown. In [11] we discuss the following features: the amplitude for each mode varies randomly with time, the total signal power in the mHz band is always significant and the cross correlations between the variations in the modal amplitudes with respect to time are almost zero. The random atmospheric excitation mechanism is preferable for the above features of the signals.

Thus, we conclude that the Earth's atmosphere can continuously excite detectable free oscillations. The amplitudes and frequency dependence of the observed signals are consistent with our theory. Mars and Venus should also exhibit observable continuously excited fundamental spheroidal-mode free oscillations excited by their atmospheres; it should be possible to use such signals to probe their internal structure.

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References

[1] Dziewonski A M and Anderson D L 1981 *Phys. Earth Planet. Inter.* **25** 297
[2] Nawa K, Suda N, Fukao Y, Sato T, Aoyama Y and Shibuya K 1989 *Earth Planets Space* **50** 3
[3] Suda N, Nawa K and Fukao Y 1998 *Science* **279** 2089
[4] Kobayashi N and Nishida K 1998 *Nature* **395** 357
[5] Goldreich P and Kumar P 1988 *Astrophys. J.* **326** 462
[6] Sagan C 1962 *Icarus* **1** 151
[7] Howard J N, Burch D E and Williams D 1956 *J. Opt. Soc. Am.* **46** 186
[8] Gilbert F 1970 *Geophys. J. R. Astron. Soc.* **22** 223
[9] Osaki Y 1989 *Progress of Seismology of the Sun and Stars* (Berlin: Springer) p 75
[10] Wielandt E and Streckeisen G 1982 *Bull. Seismol. Soc. Am.* **72** 2349
[11] Nishida K and Kobayashi N 1998 *J. Geophys. Res.* submitted