EPSC Abstracts
Vol. 8, EPSC2013-643, 2013
European Planetary Science Congress 2013

An analytical framework to classify waves on Venus

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Abstract

The dispersion relations of up to six types of atmospheric waves have been analytically obtained for the atmosphere of Venus between 45 and 80 km, using the same set of primitive equations and considering the vertical variation of the static stability and horizontal shear of the background wind. Here we determine,for the first time, the nature of the numerous waves observed with remote sensing data.

1. Introduction

The atmospheric superrotation of Venus remains an unsolved problem in geophysical fluid dynamics. Even when an agreement exists for the main role that atmospheric waves must have in the generation and maintenance of the superrotation [2], an analytical deduction of the rich diversity of atmospheric waves [9] expected on Venus has never been done [7].

2. Venus Reference Atmosphere

In order to study the waves in a wide region, we created a reference atmosphere for 45−80 km height, updating with Venus Express the data from previous missions [2,7]. In the case of the mean zonal wind, we made an interpolated map (Fig. 1) combining "in situ" [2] and cloud tracking wind measurements [4].

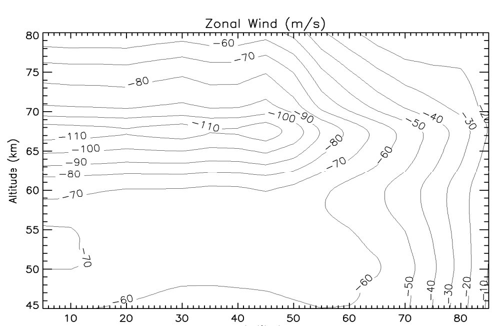

Figure 1: Background zonal wind for the reference atmosphere.

3. Waves' solutions for Venus

Conversely to the terrestrial case, the Venus atmosphere is characterized by a cyclostrophic regime where the pressure gradient is balanced by the centrifugal forces [2]. Assuming that we have neutral waves in an unbounded atmosphere that behaves as ideal gas and adiabatic, we can obtain different dispersion relations (see table 1) [7,8] from the following equations for the waves' amplitudes (zonal, meridional and vertical momentum, continuity and thermodynamic) where B,Θ,H_0,ϖ and Ψ are the static stability, potential temperature, density scale height, intrinsic and centrifugal frequencies respectively:

$$-i\varpi\cdot\hat{u}+\left(\frac{\partial u_0}{\partial y}-\Psi\right)\cdot\hat{v}+ik_x\cdot\frac{\hat{P}}{\rho_0}=0 \quad (1)$$

$$-i\varpi\cdot\hat{v}+2\Psi\cdot\hat{u}+ik_y\cdot\frac{\hat{P}}{\rho_0}=0 \quad (2)$$

$$-i\varpi\cdot\hat{w}+\frac{d}{dz}\left(\frac{\hat{P}}{\rho_0}\right)-B\frac{\hat{P}}{\rho_0}-g\cdot\hat{\Theta}=0 \quad (3)$$

$$-i\varpi\cdot\frac{\hat{\rho}}{\rho_0}+ik_x\cdot\hat{u}+ik_y\cdot\hat{v}+\frac{d\hat{w}}{dz}-\frac{\hat{w}}{H_0}=0 \quad (4)$$

$$-i\varpi\cdot\hat{\Theta}+B\cdot\hat{w}=0 \quad (5)$$

Table 1: Dispersion relations for the Venus waves

Wave type	Dispersion relation
Acoustic	$\varpi\approx\pm c_S\cdot\sqrt{k^2+m^2+\frac{1}{4\tilde{H}_0^2}}$
Inertia	$\varpi\approx\pm\xi=\pm\sqrt{2\Psi^2-2\Psi\frac{\partial u_0}{\partial y}}$
Gravity	$\varpi\approx\pm\sqrt{\frac{k^2gB}{k^2+m^2+1/4\tilde{H}_0^2}}$
Lamb	$\varpi\approx\pm\sqrt{\xi^2+k^2c_S^2}$
Surface	$\varpi\approx\sqrt{\xi^2+gH_0k^2\left(1-e^{-h_e/H_0}\right)}$
Centrifugal	$\varpi\approx\frac{-2\beta\cdot k_x}{k_x^2+k_y^2+m^2\cdot\left(\frac{2\Psi^2}{gB}\right)}$

4. Classification of Venus waves

Once the waves' solutions have been obtained, we can employ their corresponding dispersion relations to study their behavior and create dispersion graphs suitable for the wave parameters than can be directly measured with remote sensing data: the horizontal wavelength and intrinsic phase velocity for the waves apparent in cloud morphology (Fig. 2, panel above) and the periods measured in wind velocity and cloud brightness distributions (Fig. 2, panel below).

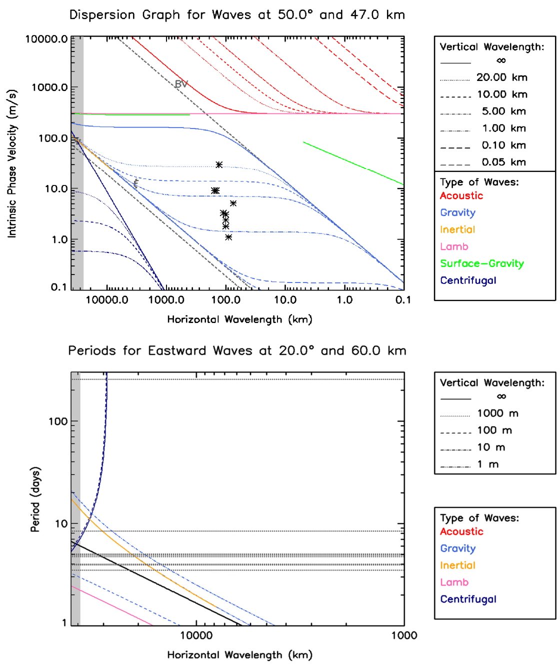

Figure 2: Dispersion graphs to classify waves as apparent in the lower clouds (asterisks extracted from [6]) and as periodicities in the winds and cloud brightness (grey lines extracted from [1,3,5]).

5. Summary and Conclusions

Under reasonable assumptions, we have analytically solved the waves' equations for Venus considering the vertical variation of the static stability and horizontal shear of the mean wind. The dispersion relations for acoustic, inertia-gravity, Lamb and surface waves have been calculated, in addition to a new type of global-scale wave of centrifugal nature and with no terrestrial analogue. These have allowed to identify, for the first time in a global manner, the many wave features measured with remote sensing by successive orbiters and flyby missions.

Acknowledgements

JP thanks support from the Portuguese Foundation for Sci.&Tech. (FCT, Grant ref.: SFRH/BPD/63036/ 2009) and the Spanish MICINN support through the CONSOLIDER program "ASTROMOL" CSD2009-00038 and project AYA2011-23552. JP, DL and PM acknowledge FCT funding through project grants POCI/CTE-AST/110702/2009, programme Pessoa-PHC and project PEst-OE/FIS/UI2751/201. AP is supported by the EU 7th Framework Programme (FP7/2007-2013) under grant agreement No. 246556. ASL is supported by AYA2012-36666 and FEDER, Grupos GV IT765-13 and UPV/EHU UFI11/55.

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