Icarus 227 (2014) 94–111

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

High latitude gravity waves at the Venus cloud tops as observed by the Venus Monitoring Camera on board Venus Express

A. Piccialli [a,b,*], D.V. Titov [a], A. Sanchez-Lavega [c,d], J. Peralta [e,f], O. Shalygina [g], W.J. Markiewicz [g], H. Svedhem [a]

[a] *ESA, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands*
[b] *LATMOS, UVSQ, 11 bd dAlembert, 78280 Guyancourt, France*
[c] *Departamento de Física Aplicada I, Escuela Técnica Superior de Ingeniera, Universidad del País Vasco (UPV-EHU), Bilbao, Spain*
[d] *Unidad Asociada Grupo Ciencias Planetarias UPV/EHU-IAA (CSIC), Spain*
[e] *IAA/CSIC, Glorieta de la Astronomía, 18008 Granada, Spain*
[f] *Observatório Astronómico de Lisboa (CAAUL), Tapada da Ajuda, 1349-018 Lisboa, Portugal*
[g] *Max Planck Institute for Solar System Research, Max Planck Strasse 2, 37191 Katlenburg-Lindau, Germany*

ARTICLE INFO

Article history:
Received 21 May 2013
Revised 12 September 2013
Accepted 16 September 2013
Available online 25 September 2013

Keywords:
Venus
Atmospheres, dynamics

ABSTRACT

High resolution images of Venus Northern hemisphere obtained with the Venus Monitoring Camera (VMC/VEx) allow studying small-scale dynamical phenomena at the cloud tops (∼62–70 km altitude) including features like wave trains. A systematic visual search of these waves was performed; more than 1500 orbits were analyzed and wave patterns were observed in more than 300 images. Four types of waves were identified in VMC images on the base of their morphology: long, medium, short and irregular type waves. With the aim to characterize the wave types and their possible excitation source, we retrieved wave properties such as location (latitude and longitude), local time, solar zenith angle, packet length and width, orientation, and wavelength of each wave. The long type waves appear as long and narrow straight features extending more than a few hundreds kilometers and with wavelengths between 7 and 17 km. Medium type waves exhibit irregular wavefronts extending more than 100 km and with wavelengths in the range 8–21 km. Short wave packets have a width of several tens of kilometers and extend to few hundreds kilometers and are characterized by smaller wavelengths (3–16 km). Irregular wave fields appear to be the result of wave interference. The waves are often identified in all VMC filters and are mostly found in the cold collar region at high latitudes (60–80°N) and are concentrated above Ishtar Terra, a continental size highland that includes the highest mountain belts of the planet. The high speed of the Venus Express spacecraft close to the pericentre does not allow to measure phase speed of waves due to the short temporal interval between image pairs. The lack of information on phase velocities does not allow us to establish with absolute confidence the nature of these waves. However, by comparing the morphology and properties of the wave features observed in VMC images to those seen by previous observations it is reasonable to assume that the waves studied here are gravity waves.

1. Introduction

A gravity wave is a wave disturbance in which buoyancy acts as the restoring force. It can only exist in a stably stratified atmosphere and can be triggered for example by convection below or by horizontal flow passing an obstacle. Gravity waves manifest themselves as regular cloud structures or quasi-periodic disturbances on the atmospheric temperature profiles. An example is given by the lee waves formed when a stable air flow passes over a mountain (Holton, 2004). Gravity waves are very important since they can transport energy and momentum by propagating both vertically and horizontally within the atmosphere (Holton, 2004) and they could be playing an important role in the maintenance of the atmospheric circulation on Venus (Hou and Farrell, 1987; Lebonnois et al., 2010). Gravity waves are a common feature in the mesosphere of terrestrial planets (Sanchez-Lavega, 2011). On Earth, gravity waves frequently reveal their presence through cloud formations, such as in the case of lee waves forced by topography (Sanchez-Lavega, 2011). At higher altitudes, images of polar mesospheric clouds, also known as noctilucent clouds, often show distinct wave-like structures likely due to upward propagating and

* Corresponding author at: LATMOS, UVSQ, 11 bd dAlembert, 78280 Guyancourt, France.

E-mail addresses: arianna.piccialli@latmos.ipsl.fr (A. Piccialli), dmitri.titov@esa.int (D.V. Titov), agustin.sanchez@ehu.es (A. Sanchez-Lavega), peralta@iaa.es (J. Peralta), shalygina@mps.mpg.de (O. Shalygina), markiewicz@mps.mpg.de (W.J. Markiewicz), hsvedhem@rssd.esa.int (H. Svedhem).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.09.012

breaking gravity waves (Chandran et al., 2009). In the martian atmosphere, direct evidence of gravity waves is found on mesospheric CO_2 ice clouds observed by the High Resolution Stereo Camera and the imaging spectrometer OMEGA on board Mars Express (Määttänen et al., 2010), as well as by the Mars Odyssey spacecraft's Thermal Emission Imaging System (McConnochie et al., 2010). Fluctuations interpreted as gravity waves were identified in temperatures measured by the Galileo Atmosphere Structure Instrument (ASI) in Jupiter's stratosphere (Young et al., 2005) and gravity waves have also been detected at Jupiter's equator at cloud level (Arregi et al., 2009). Ultraviolet images of the Venus cloud tops acquired by Mariner 10 and Pioneer Venus showed cloud features typically between 200 and 1000 km in size which were interpreted as gravity waves (Belton et al., 1976; Rossow et al., 1980). Vertical propagating gravity waves with a vertical wavelength of 6 to 8 km were detected in the temperature and wind profiles acquired by the four Pioneer Venus Probes (Seiff et al., 1980; Counselman et al., 1980). Evidence for the existence of small scale waves comes also from radio occultation temperature retrievals obtained by the Pioneer Venus (Kliore and Patel, 1980), the Venera 9 (Kolosov et al., 1980), and the Magellan spacecrafts (Hinson and Jenkins, 1995).

More recently, several experiments on board the European mission Venus Express (VEx) (Svedhem et al., 2007) have reported detection of waves in the Venus atmosphere both as oscillations on the temperature field and as patterns on the cloud layer (Wilson and Piccialli, 2012; Titov et al., 2012). Venus Express provides an observational data base on waves in the Venus atmosphere due to long duration of the mission, the highly elliptical orbit that enables both distant and close-up observations, and powerful payload that in particular provides systematic high resolution imaging and frequent temperature sounding with high vertical resolution by radio-occultations (Titov et al., 2006; Svedhem et al., 2007). Waves were observed at different latitudes and altitudes, on both day and night. Small-scale temperature fluctuations originating from internal gravity waves with vertical wavelengths of only a few kilometers were detected in temperature profiles retrieved by the Venus Express Radio-Science Experiment VeRa (Tellmann et al., 2012). Images acquired by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS/VEx) display gravity waves with horizontal wavelengths of 60–150 km in the upper cloud (~66 ± 4 km altitude) in the dayside hemisphere and in the lower cloud (~44–48 km altitude) in the nightside hemisphere (Peralta et al., 2008). In the Venus upper atmosphere (110–140 km altitude) gravity waves with horizontal wavelengths in the 90–400 km range were revealed by non-LTE CO_2 emissions observed by VIRTIS/VEx (Garcia et al., 2009). High resolution images of Venus Northern hemisphere obtained with the Venus Monitoring Camera (VMC/VEx) allow to study small scale features like wave trains (Markiewicz et al., 2007b; Titov et al., 2012). In this paper we present a detailed statistical analysis of the wave properties aimed to characterize the wave types and their possible origin.

2. Observations and dataset

The Venus Monitoring Camera (VMC) on board Venus Express is a CCD-based camera specifically designed to take images of Venus in four narrow band filters in ultraviolet (UV – 365 nm), visible (VIS – 513 nm), and near-infrared (N1 – 965 and N2 – 1000 nm). A detailed description of the VMC instrument as well as its scientific objectives can be found in Markiewicz et al. (2007a). The first results of the VMC observations were presented by Markiewicz et al. (2007c). Titov et al. (2012) gave detailed description of the VMC in-flight performance and observations related to the cloud morphology and waves.

Venus Express orbit allows VMC to acquire global views of the Venus Southern hemisphere when the spacecraft is at apocentre and in the ascending arc of the orbit at a distance of 60,000–26,000 km from the planet (Fig. 1 top). Apocentric images are used to study near-polar global dynamics. In the ascending branch of the

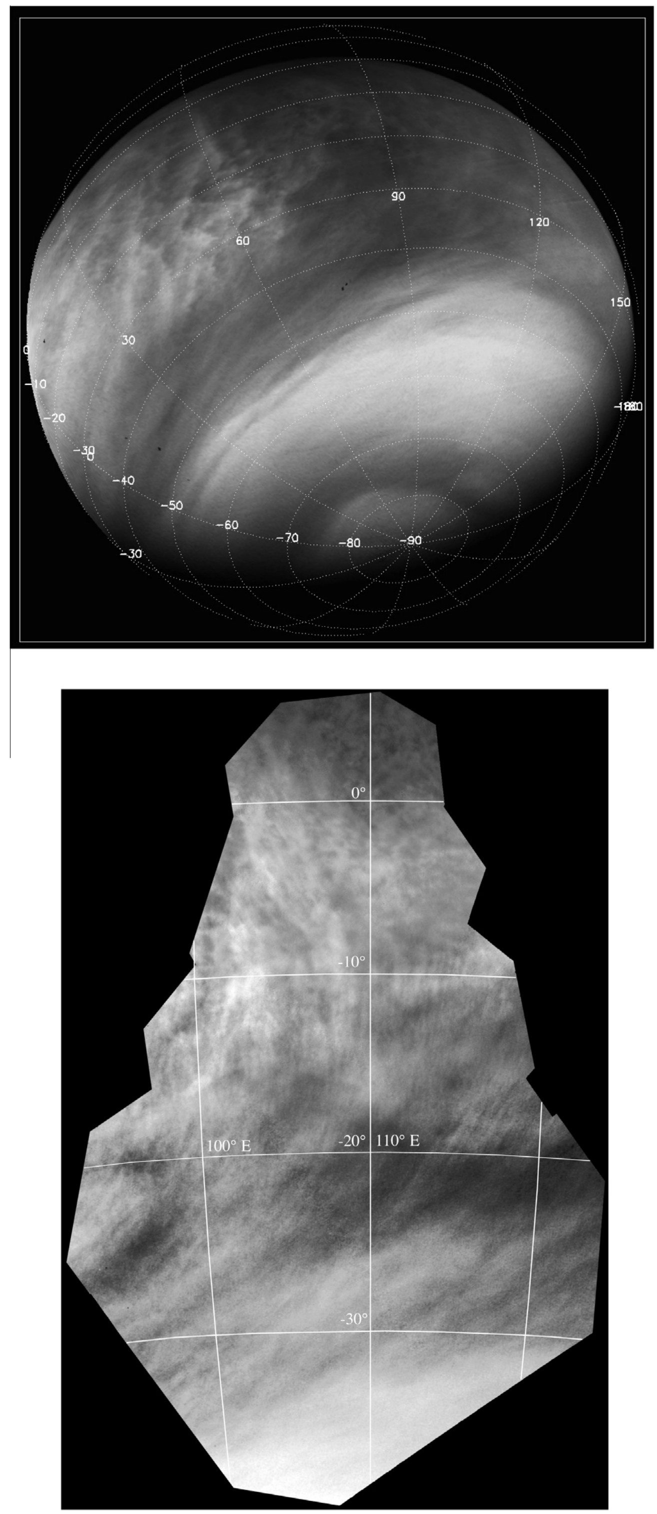

Fig. 1. VMC UV images of Venus: (top) global view, (bottom) mosaic of Venus cloud tops obtained by combining several images taken at distances from 5000 to 1000 km from the planet (Copyright ESA).