CHARACTERISTICS OF INDIVIDUAL INTERNAL GRAVITY WAVES IN THE MARTIAN ATMOSPHERE OBTAINED FROM *MARS GLOBAL SURVEYOR* RADIO OCCULTATION DATA: EVIDENCE FOR WAVE SATURATION.

V. N. Gubenko, I. A. Kirillovich, A. G. Pavelyev and V. E. Andreev, Kotelnikov Institute of Radio Engineering and Electronics of the RAS, Vvedenskogo square 1, 141190 Fryazino, Moscow region, Russia, e-mail: vngubenko@gmail.com

Introduction: An original method of determining the characteristics of an internal gravity wave (IGW) has been developed using the data of an analysis of individual vertical temperature or buoyancy frequency square profile in the planet's atmosphere. A threshold criterion of IGW identification is formulated and justified, by which, analyzed fluctuations can be considered as wave manifestations. [1–3]. The method is based on an analysis of relative wave amplitude determined from the vertical temperature profile, as well as on the assumption of the IGW linear theory, according to which the wave amplitude is limited by the processes of dynamic (shear) instability in the atmosphere. It is supposed that, when the amplitude of the internal wave reaches the shear instability threshold as the wave propagates upward, a dissipation of wave energy occurs such that the IGW amplitude is maintained at the atmospheric instability threshold. The application of the developed method to vertical temperature profiles obtained from radio occultation (RO) measurements of the *Mars Global Surveyor* (*MGS*) mission made it possible to identify IGWs in the Martian atmosphere and determine the values of key wave parameters such as intrinsic frequency, amplitudes of the vertical and horizontal disturbances of wind velocity, vertical and horizontal wavelength, intrinsic vertical and horizontal phase (and group) velocities, kinetic, potential, and total energy of IGWs per unit mass, vertical fluxes of wave energy and horizontal momentum [4]. Identified in the Martian atmosphere IGWs, with a vertical wavelength of 4.5–8.2 km, are waves with low intrinsic frequencies close to inertial frequency. Their kinetic energy, as a rule, is greater than potential energy by an order of magnitude. The propagation of these waves causes a significant modulation of the stability of atmospheric stratification that leads to shear instability and the occurrence of thin layers of intermittent turbulence in the Martian atmosphere.

Experimental data for an analysis: The data on the vertical temperature profiles of the *MGS* mission were taken by us from NASA' archive of the planetary data system (http://starbrite.jpl.nasa.gov/pds/…, Planetary Data System) and they are the primary material for processing and analysis in order to identify IGWs and reconstruct wave characteristics in the Martian atmosphere. The vertical resolution of these temperature profiles, which depends on the geometry of the experiment and the wavelength of the sounding signal, is limited by diffraction effects and is ~1 km. Near the planet's surface, where the restored profiles are most accurate, the standard deviation of temperature fluctuations is equal to about 0.4 K, which corresponds to the value of relative data spread of ~0.2% [5]. The vertical resolution of the temperature data was significantly different for different profiles, but it was not worse than 1250 m [6]. Therefore, to ensure consistency in data processing and to simplify the spectral analysis of investigated fluctuations, the altitude interpolation of temperature values was performed each 1250 m. The high-frequency filtration of temperature fluctuations with a cutoff at 10 km allowed us to exclude structures with the vertical wavelengths more than 10 km, which may not be caused by IGWs but instead by thermal tides, occurring most often in the atmosphere above the mountains, particularly over the Tharsis region [6]. At the next step of data processing, the method of an analysis of wave manifestations and IGW parameter determination was applied to the vertical temperature profiles. As can be seen from [1–3], in the case of a positive identification of IGWs, we can determine key wave parameters such as the intrinsic frequency, amplitudes of vertical and horizontal disturbances of wind velocity, vertical and horizontal wavelength, intrinsic vertical and horizontal phase velocities, density of kinetic, potential, and total energy, vertical fluxes of wave energy and horizontal momentum, and others. For the further analysis of profiles in order to identify wave events, we have selected vertical profiles where noticeable quasi-periodic temperature variations were observed, and intervals of wave observation were determined for each of the selected profiles [4].

Figure 1 shows an example of altitude profiles of variations of temperature and square of the buoyancy frequency in the range of 8–26.5 km restored from the measurements of the *MGS* mission on 19 May 1999 in the Martian atmosphere. The indicated measurements were performed during the Martian summer (L_s = 141.03°) at 4:10 of local time in the atmospheric region with coordinates 18.11° N and 112.65° W (data file: 9139G18A.TPS) located above the Tharsis mountain volcanic massif. Powerful quasi-periodic variations of T and N^2 with a vertical wavelength of ~6.6 km are identified as manifestations of saturated IGW in the planet's atmosphere. Two independent estimates of the wave amplitude, a_e= 0.95 and A^{rel}_{N2} = 1, in good agreement with each other, testify that the saturation degree of the wave amplitude is not less than 95%, since for saturated IGW with any intrinsic frequency ω, the relative threshold amplitude does not exceed one. The intrinsic frequency of the internal wave is greater than the inertial frequency approximately by a factor of 2.4 (f/ω = 0.42), and its kinetic energy is greater than potential energy by a factor of 1.4. It is seen from Fig. 1 that IGW propagation leads to a strong modulation of the stability of atmospheric stratification. Local values of parameter N^2 reach zero near levels of 9, 15, and 21 km, which assumes here not only dynamic, but also convective instability, and the occurrence of thin layers of intermittent turbulence in the atmosphere. These thin layers of turbulence having a thickness significantly less than λ_z and a horizontal extent of the order of magnitude of λ_h cannot destroy the structure of the wave field [4].

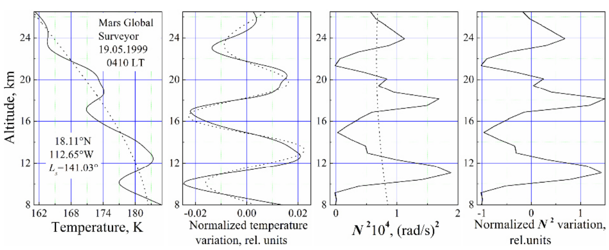

Figure 1. Manifestation of the fully saturated IGW (sat. degree ≥ 0.95) in the Martian atmosphere (Tharsis region) from the vertical temperature profile (data file: 9139G18A.TPS) retrieved from *MGS* RO on 19 May 1999. The season was summer in the northern hemisphere (celestial longitude L_s =141.03°) and the local true solar time was 04:10 h, corresponding to early morning. Wave parameters: λ_z=6.6 km; λ_h=580 km; E=42,7 J/kg; $p=E_k/E_p$=1.4; E_p=17.6 J/kg; f/ω=0.42; T^{in}=2π/ω=16.6 hrs; a_e=0.95; $|u'|$=9.2 m/s; $|v'|$=3.9 m/s [4].

Figure 2 shows a rare example of so-called "clean" wave observations, where noise was not discovered in the spectrum of analyzed temperature fluctuations. Coordinates of the probing atmospheric region and information about the time of the measurements are shown in Fig. 2. Quasi-periodic variations of T and N^2 with a vertical wavelength of ~4.5 km have been identified as signatures of propagation of inertial IGW in the Martian atmosphere. The intrinsic frequency of the internal wave is close to the inertial frequency (f/ω = 0.89), and its kinetic energy is greater than potential energy by a factor of 8.4. The very good correspondence of the values of the wave parameters reconstructed by two different ways should be noted. We find that the value A^{rel}_{N2} = 0.63 coincides with the estimate of the wave amplitude a_e obtained from an analysis of the temperature data. A comparison shows that the results of reconstruction of the IGW parameters obtained by two different methods are practically identical [4].

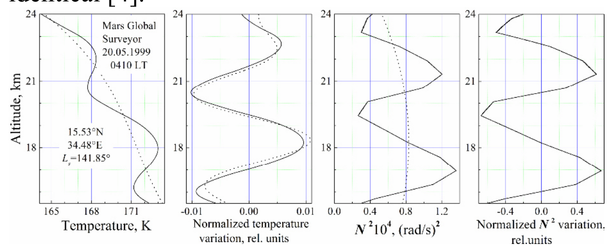

Figure 2. The same as Figure 1 except from radio occultation (data file: 9140V32A.TPS) conducted in summer (L_s=141.85°) at 04:10 h LT on 20 May 1999. Example of "clean" wave observations, where noise was not discovered in the spectrum of analyzed temperature fluctuations. Wave parameters: λ_z=4.5 km; λ_h=2080 km; E=39.9 J/kg; $p=E_k/E_p$=8.4; E_p=4.2 J/kg; f/ω=0.89; T^{in}=2π/ω=40.7 hrs; a_e=0.63; $|u'|$=8.9 m/s; $|v'|$=7.9 m/s [4].

Conclusion: An original method of identifying internal waves and determining their characteristics has been developed based on the analysis of the vertical temperature or buoyancy frequency square profile in the planet's atmosphere. Application of the method to the analysis of the vertical temperature profile of the *MGS* mission enables the identification of IGWs in the Martian atmosphere and the determination of the values of key wave parameters such as intrinsic frequency, amplitudes of the vertical and horizontal disturbances of wind velocity, vertical and horizontal wavelength, density of kinetic and potential energy, vertical fluxes of wave energy and horizontal momentum. IGWs with vertical wavelength of 4.5–8.2 km identified in the Martian atmosphere are waves with low intrinsic frequencies close to the inertial frequency, and their kinetic energy, as a rule, exceeds potential energy by an order of magnitude. The propagation of these waves causes a significant modulation of the vertical stability of atmospheric stratification that leads to shear instability and the occurrence of thin layers of intermittent turbulence in the Martian atmosphere.

Acknowledgments: This work was partially supported by the Program no. 7 of the RAS Presidium.

References: [1] Gubenko V. N. et al. (2008) *JGR, 113,* D08109. [2] Gubenko V. N. et al. (2011) *AMT, 4,* 2153–2162. [3] Gubenko V. N. et al. (2012) *Cosmic Res., 50,* 21–31. [4] Gubenko V. N. et al. (2015) *Cosmic Res., 53,* 133–142. [5] Hinson D. P. et al. (2001) *JGR, 106,* 1463–1480. [6] Creasey J. E. et al. (2006) *JRL, 33,* L01803.