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MODAL FREQUENCIES OF IONOSPHERIC PERTURBATIONS INDUCED BY SOLAR WIND IMPACTS

V. ČADEŽ[1], D. ŠULIĆ[2] and V. SREĆKOVIĆ[3]

[1]*Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia*
E–mail: vcadez@aob.bg.ac.rs

[2]*Institute of Physics, Pregrevica 118, Box 57, 11001 Belgrade*
E–mail: dsulic@phy.bg.ac.rs

[3]*Institute of Physics, Pregrevica 118, Box 57, 11001 Belgrade*
E–mail: vladimir.sreckovic@phy.bg.ac.rs

Abstract. Solar activity phenomena such as flares and coronal mass ejections (CME) may result into sudden and pronounced variations of the solar wind parameters which are then conveyed away into the interplanetary space with characteristic speeds. At the location of the solar wind impingement on the geomagnetic field, this perturbs the whole magnetosphere-ionosphere system forcing it to oscillations. In this work, we argue that corresponding modal frequencies can be deduced from spectral analyses of registered real time variations of amplitudes and phases of VLF (very low frequency) radio-waves.

1. INTRODUCTION

The geomagnetic field and the ambient plasma acts as a quasi-elastic shield against the solar wind particle flow. Any variations in the solar wind structure resulting from solar activity, the coronal mass ejections (the CMEs) in particular, perturb the topology of the magnetosphere and the adjacent ionosphere. The resulting effects are various types of oscillations with eigen-frequencies typical of physical properties of the local plasma primarily the magnetic field and charged particle concentrations.

The solar-wind induced magnetospheric-ionospheric oscillations are expected to be of the Alfvén wave type modified by the curvature of the geomagnetic field, i.e. to be latitude dependent. In this sense, the oscillation frequencies are lower at the equatorial regions and are increasing toward higher latitudes (see Jacobs 1970, Baumjohann et al. 1997).

The mechanism of the solar wind interaction with the geomagnetic field is not a single process; rather, there are several scenarios for it. First, the arrival of a sudden jump in physical parameters of the solar wind acts as an additional temporal mechanical force hitting and perturbing the day-side of the geomagnetic system forcing it to oscillate. Next, even a quiet solar wind that flows along the geomagnetic field lines causes the Kelvin-Helmholtz instability and the resulting waves in the magnetosphere that can be felt in the ionosphere to. Finally, a resonant excitation of Alfvén waves in the non-uniform magnetospheric plasma results into a local excitation of Alfvén waves (De Keyser 2001a, 2001b). Fig. 1 shows the international classification of such oscillations according to their frequency and origin.

	Pulsation classes						
	Continuous pulsations					Irregular pulsations	
	Pc 1	Pc 2	Pc 3	Pc 4	Pc 5	Pi 1	Pi 2
T [s]	0.2-5	5-10	10-45	45-150	150-600	1-40	40-150
f	0.2-5 Hz	0.1-0.2 Hz	22-100 mHz	7-22 mHz	2-7 mHz	0.025-1 Hz	2-25 mHz

Figure 1: Classification of ionospheric pulsations.

In addition to the mentioned mechanisms that are based on magnetic forces, there is an additional way of perturbing the ionosphere that results from a varying solar radiation flux responsible for ionization processes and formation of ionization layers in the ionosphere. As seen in Fig. 2, sudden changes in intensity of the ionizing solar radio flux alters the location, i.e. the height of the ionization layer.

2. GEOMAGNETIC PULSATIONS AND RADIO WAVE PROPAGATION

In this paper, we argue that the described perturbations of the coupled system magnetosphere-ionosphere can be observed by analyzing the time variation of recorded single frequency radio waves in the VLF band (18-24 kHz in our case). In particular, in the Institute of Physics, Belgrade, Serbia, we monitor the time variation of the amplitude $A(t)$ and phase $\phi(t)$ of VLF radio waves $\mathcal{E}(t) = A(t)\sin[2\pi\nu_w t - \phi(t)]$ emitted from a network of transmitters at different locations on the Earth.

Radio waves emitted from faraway emitters can not reach the receiver in Belgrade directly along a straight line of sight; rather, they follow a longer trajectory that involves multiple wave reflections from the ionospheric layer and ground. The length of the wave trajectory thus varies in time in the same way as the height of the wave reflection $\mathrm{h}_r(\mathrm{t})$ changes due to geomagnetic disturbances. This is depicted schematically in Fig. 2 where the wave reflection hight $\mathrm{h}_r(\mathrm{t})$ follows from the condition for the emitted wave frequency ν_w:

$$\nu_w \cos(\theta) = \nu_p(n_e(h_r))$$

where θ is the vertical angle of the emission and ν_p is the standard electron plasma frequency in Hz. Due to geomagnetic perturbation processes the electron concentration n_e varies in time and so does the electron plasma frequency $\nu_p = 8.98 \times 10^3 \mathrm{n}_e^{1/2}\mathrm{Hz}$ which causes the above frequency matching condition to occur at varying heights $h_r(t)$.

Now, if the recorded time dependences of the radio wave amplitude $A(t)$ and phase $\phi(t)$ are Fourier transformed

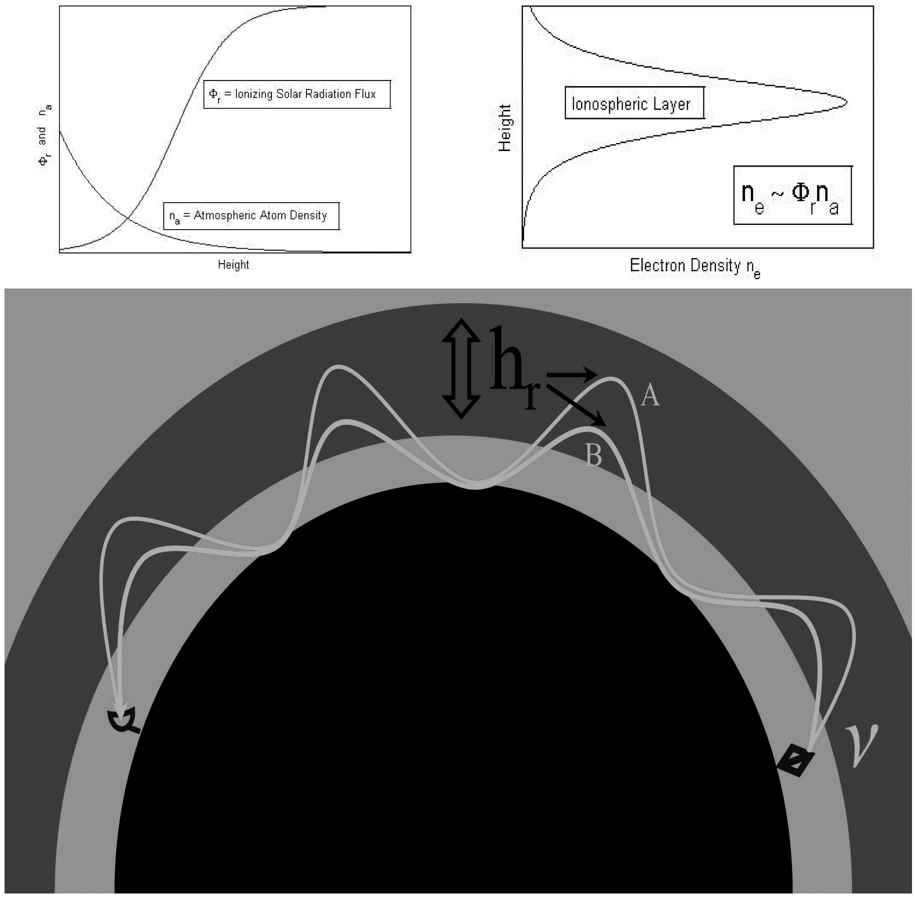

Figure 2: Schematic formation of ionospheric layers and the ray path of reflected radio waves emitted of the Earth.

$$A_F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathrm{e}^{-\omega \mathrm{t}} \mathrm{A(t)dt}, \quad \text{and} \quad \phi_\mathrm{F}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathrm{e}^{-\omega \mathrm{t}} \phi(\mathrm{t})\mathrm{dt}, \tag{1}$$

where $\omega = 2\pi\nu = 2\pi/T$ (T=oscillation period), their frequency spectra $A_F(\omega)$ and $\phi_F(\omega)$ should recover the global and local pulsations as well as some transient oscillations of the geomagnetic field.

Temporal variations of a recorded radio signal strongly depend on local physical conditions along its path between the emitter and receiver. Fig. 3 shows such differences which are clearly less pronounced for waves emitted from UK (GQD 22.1 kHz) and France (HWU-18.3 kHz) as their trajectories are similar while the radio waves emitted in the USA (NAA 24.0 kHz) have significantly different time variation when recorded in Belgrade.

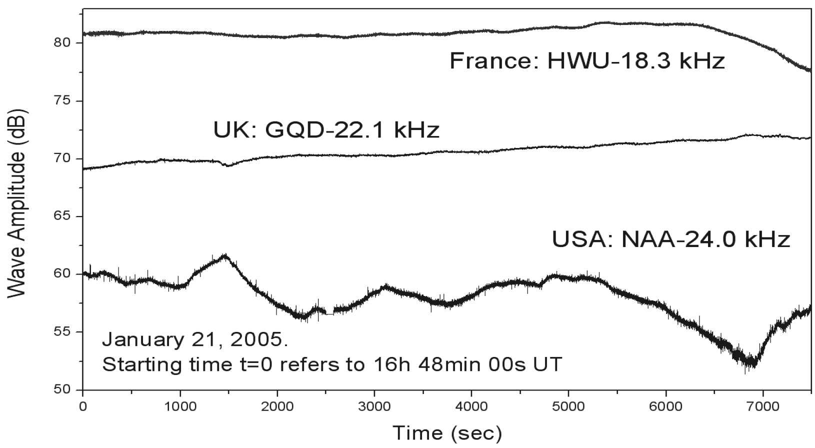

Figure 3: Amplitudes of VLF radio waves emitted from three different locations recorded in Belgrade.

Two radio wave parameters that we monitor in time are the wave amplitude and wave phase and they exhibit some similarities of their time-dependencies as seen in Fig. 4. However, these two parameters also have their own peculiarities coming from the physical background: The phase variations are related to changes of the length of the wave trajectory which is further related to variations of the height of the wave reflection in the ionospheric layer while the amplitude may change also due to altered wave absorption conditions, wave scattering etc.

3. SPECIAL EXAMPLE

As an example of the radio wave spectral analysis we show the case of a strong CME that erupted on July 20, 2004 during the intense solar activity at 14-18h UT. It took about two days for the CME disturbance to arrive to the Earth and induce perturbations in the geomagnetic field which effected radio-wave propagations. In Fig. 4 we see a sudden change in both the amplitude and phase time variation of the VLF radio wave with frequency of 24.0 kHz emitted by the NAA transmitter in Main, USA which occurred at about 9h 07min UT. Such a shock-like disturbance forced the geomagnetic field and the ionosphere to additional oscillations typical of physical properties of local magnetic field and plasma along the trajectory of the recorded radio signal.

To obtain the induced new frequencies in the existing geomagnetic-ionospheric oscillation spectra we took the registered data for the phase variation of the 24.0 kHz VLF wave emitted in Main, USA with the cadence of 0.1 sec for a time interval of some two hours, between 8h 24min and 10h 30min UT. This time interval thus includes signatures of the geomagnetic dynamics before and also after the CME induced solar wind gust hit the outer regions of the magnetosphere as seen in the upper plot in Fig. 5. Bearing this in mind, we divided the interval into two parts: Part one for $0 \leq t \leq 3000$s that covers the situation prior the solar wind gust impact and

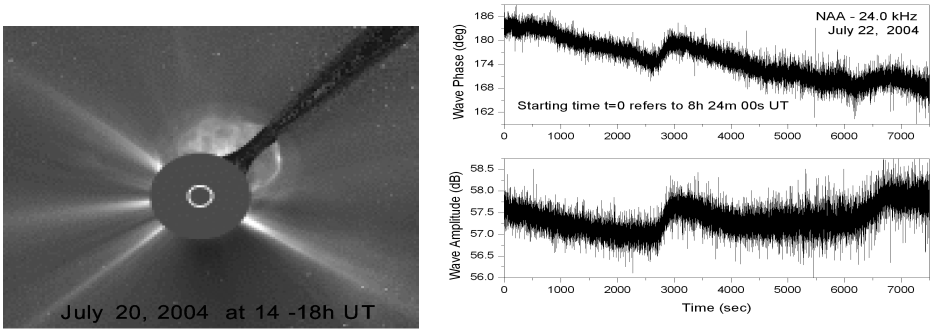

Figure 4: An example of a coronal mass ejection - CME - and the resulted radio wave amplitude and phase disturbance as recorded in Belgrade two days after the CME.

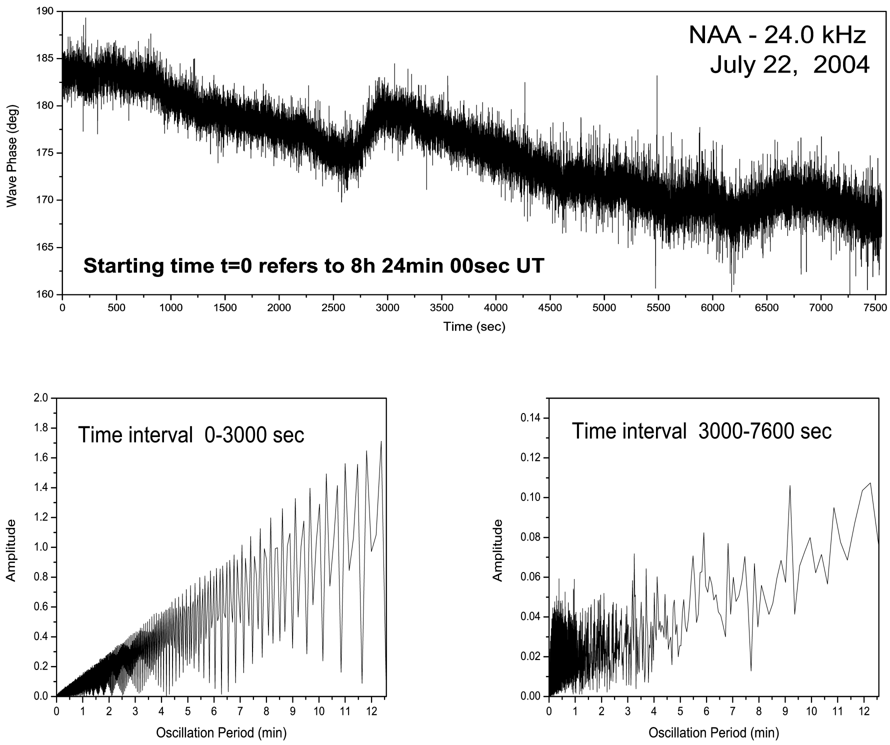

Figure 5: The wave phase variation in time and its Fourier spectra over two indicated time intervals. The data are for a wave emitted by the NAA transmitter in Main, USA. A solar-wind induced disturbance is noticeable at t≈2600 s.

part two for $t \geq 3000$s which includes data related to the newly perturbed system magnetosphere-ionosphere. Each of the two intervals is then Fourier analyzed and a part of the resulting frequency spectra is shown in the lower part in Fig. 5 as plots of Fourier transform amplitudes versus oscillation period. It is clearly seen that after the impact (interval $t \geq 3000$s), among other features, some particular oscillations appear with periods of multiple of 3 min between 3 min and 12 min which indicates a possible presence of excited eigen modes in the perturbed geomagnetic system. These oscillation periods fall within the irregular pulsations Pc5 and Pi2 according to the classification in Fig. 1.

Here, we do not intend to go further into more detailed analyses of various other features of recorded VLF radio waves that can be studied with the aim of understanding local and global structures, mutual coupling of the magnetosphere and ionosphere, and how the whole geomagnetic system reacts to transient solar wind and radiation variations induced by the solar activity.

To conclude, we find challenging to proceed with a systematic study of the VLF radio data obtained by our local receiver in the Institute of Physics, Belgrade, Serbia which should provide us with new insight into the global and local structures and behavior of the geomagnetic field and the ionosphere in interaction with the solar wind. Such a study can be considered as a method complementary to other standard means of investigation utilized in the aeronomy.

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