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WAVES FROM THE SUN: TO THE 100th ANNIVERSARY OF V.A. TROITSKAYA'S BIRTH

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Abstract. It has been one hundred years since the birth of the outstanding scientist Professor V.A. Troitskaya. Her remarkable achievements in solar-terrestrial physics are widely known. For many years, Valeria A. Troitskaya was the President of the International Association of Geomagnetism and Aeronomy. This article deals with only one aspect of the multifaceted creative activity of V.A. Troitskaya. It relates to the problem of sources of ultra-low frequency (ULF) electromagnetic oscillations and waves outside Earth's magnetosphere. We were fortunate to work under the leadership of V.A. Troitskaya on this problem. In this paper, we briefly describe the history from the emergence of the idea of the extramagnetospheric origin of dayside permanent ULF oscillations in the late 1960s to the modern quest made by ground and satellite means for ULF waves excited by solar surface oscillations propagating in the interplanetary medium and reaching Earth.

Keywords: geoelectromagnetic oscillations, ultra-low frequency, Alfvén waves, magnetosphere, solar wind, interplanetary magnetic field, helioseismology.

This year we celebrate centenary of the birth of Valeria Alekseevna Troitskaya (1917–2010). Her outstanding achievements in solar-terrestrial physics are widely known. Her efforts in organizing and conducting international studies of the geoelectromagnetic field were highly appreciated by the global scientific community. For many years, Valeria Troitskaya was the President of the International Association of Geomagnetism and Aeronomy.

We deal with only one aspect of the multifaceted creative activity of Professor V.A. Troitskaya. It refers to the problem of the origin of ultralow-frequency (ULF) electromagnetic oscillations and waves. We were fortunate to work under the leadership of V.A. Troitskaya on this problem. We clearly remember the congenial intellectual atmosphere she was able to create in the research team, helping us during scientific inquiries and participating in our joy of successful discoveries.

Ground and satellite observations indicate a rich variety of ULF oscillations ranging from millihertz to several hertz. There are permanent and sporadic, narrowband and broadband oscillations. They can be global, regional, and local. Sources of the oscillations can reside in the earth's crust, in the atmosphere, ionosphere, magnetosphere, as well as outside the magnetosphere in the solar wind ahead of Earth's bow shock. Just as Carl Linnaeus introduced his system of naming and classifying plants, Valeria Troitskaya conceived the idea of systematizing ULF oscillations to arrange the variety of types and forms of experimentally observed oscillations [Troitskaya, 1964]. Together with researchers at the Borok Geophysical Observatory (GO Borok) of the Institute of Physics of the Earth of the USSR Academy of Sciences, she used the morphological principle as the basis for the classification and introduced a binomial nomenclature. All types of oscillations are divided into two classes, abbreviated to Pc (regular oscillations, *pulsations continuous*) and Pi (irregular oscillations, *pulsations irregular*). They are symbolized by PcN (N=1, ..., 5) or PiN (N=1, 2). The number N corresponds to the number of the subrange of the general ULF range (for more detail, see the reviews [Troitskaya, Guglielmi, 1967; Troitskaya, Guglielmi, 1969a] and the monographs [Jacobs, 1970, Guglielmi, Troitskaya, 1973; Nishida, 1978]). The geophysical community has adopted this systematics. It is still widely used in literature, providing insight into the rich variety of ULF oscillations of terrestrial and cosmic origin (see, e.g., [Guglielmi, Pokhotelov, 1996; Kangas et al., 1998; Lundin, Guglielmi, 2006; Guglielmi , 2007; Sivokon, 2011]).

The most significant scientific results extending knowledge about near-Earth space were obtained by V.A. Troitskaya and her team in the second half of the past century. None of the results has lost relevance today. Some of them led to the formulation of complex issues that geophysicists are still interested in. Efficiency of the research carried out by V.A. Troitskaya and her scientific team is explained primarily by a rational system of methods. They relied on a general approach to formulation and solution of problems, which was close to the well-known system approach. First, it represents oscillatory systems of Earth's magnetosphere as a comprehensive system of structured objects interacting with each other and with the environment. Second, the approach is characterized by the fact that the discovery of empirical regularities during experimental research is considered only as a necessary step to understanding, i.e., ultimately to the construction of physico-mathematical models of oscillation processes.

By the late 1960's, many contradictions and inconsistencies have been accumulated in the theory of Pc3 pulsations. It should be said that, in a certain sense, Pc3 is the main type of ULF oscillations. They constantly occur in the range of periods between 10 and 45 s on the sunlit side. These oscillations were thought to be standing magnetosonic waves with nodes at the magnetopause and on Earth's surface. This generally accepted view at that time is reflected in all papers on the subject as well as in the reviews [Troitskaya, Guglielmi, 1967, 1969a,b, 1970] and in the monograph [Jacobs, 1970]. In other words, Pc3 were considered as resonant oscillations in the open magnetosonic resonator. However, there are no resonant oscillations of this type because both reflecting boundaries are convex in the same direction. Besides this inherent contradiction of the theory, there was a discrepancy between the theory and observations. The point here is as follows. Waves were considered not to penetrate into the magnetosphere from the solar wind, experiencing total internal reflection at the magnetopause. Accordingly, Pc3 sources were modeled as surface waves excited at the magnetopause due to the Kelvin-Helmholtz instability. However, the peak Pc3 amplitude is observed during the prenoon hours, while the Kelvin-Helmholtz instability theory predicts its peaks for morning and evening hours.

To eliminate the contradictions and inconsistencies and to understand the origin of Pc3, we, rejecting the idea of complete internal reflection of waves penetrating into the magnetopause from the solar wind, have put forward a hypothesis of Pc3 excitation in the foreshock region adjacent from outside to Earth's bow shock and have developed a test that allows us to test our hypothesis by comparing the interplanetary magnetic field (IMF) with ground-based observations of Pc3 [Guglielmi, Troitskaya, 1973] (see also [Potapov, 1974; Guglielmi, 1974]). The test has the form $f=gB$, where f is the oscillation frequency from ground-based observations and B is the magnetic field modulus from observations in the interplanetary medium. Our theory suggests the following value of the coupling coefficient: $g\approx6$ mHz/nT. Let us pay attention to a peculiarity of this formula: it predicts a non-local relation between f and B. In other words, to test the hypothesis, we have to measure physical quantities at two points far apart. The typical spacing is a minimum of 100 thousand km. The test gives a positive result. First, the Pc3 frequency is directly proportional to the IMF magnitude. Second, the measured proportionality coefficient $g=5.8 \pm 0.3$ mHz/nT almost coincides with the theoretical estimate $g\approx6$ mHz/nT.

The idea of the extramagnetospheric origin of Pc3 aroused interest among Russian and foreign geophysicists. It was immediately taken up, gained in popularity, generated extensive literature, and sparked discussions that did not subside until the late 1980s. For example, the monograph [Nishida, 1978] testifies to the sharpness of the polemics and to the polarity of views. Its author, the well-known magnetologist Atsuhiro Nishida, was a staunch opponent of our theory. In this connection we should note that at present the theory of extramagnetospheric origin of Pc3 is generally accepted.

Not only Earth, but other planets of the Solar System have sufficiently powerful magnetic fields. It is clear that they also have wave structures similar to Pc3. Russel and Hoppe [1983] have found an f dependence on B from satellite measurements ahead of fronts of the magnetospheres in Mercury, Venus, Earth, and Jupiter. It turned out that up to measurement errors, the data falls on the line $f=gB$, with g close to 5.8 mHz/nT. In other words, it is the same dependence that we predicted theoretically and then justified experimentally from Pc3 observations at the GO Borok of the Institute of Physics of the Earth of the USSR Academy of Sciences. This is a surprising result. Solar wind flow conditions for the planets vary greatly. Thus, the radius of curvature of the shock front in Mercury is 0.5, whereas in Jupiter it is 500 (in Earth's radii) The mean angle between solar plasma flow direction and IMF lines increases from 20° in Mercury to 80° in Jupiter. Plasma concentration and IMF magnitude vary significantly from planet to planet. Nevertheless, the coefficient g from observations in the vicinity of the planets is the same as from observations of Pc3 on Earth. Thus, the coupling coefficient g is universal, i.e. it is relatively stable in an extremely wide range of variations in parameters of the solar wind flow around the planets.

Encouraged by the success in interpreting Pc3, Valeria Troitskaya someday, on returning from an international conference, asked us as to whether not only Pc3, excited just before the front of the magnetosphere, but also magnetohydrodynamic waves, excited on the Sun, can penetrate into the magnetosphere and contribute to the spectrum of ULF oscillations observable on Earth. According to her story, the idea struck her after a discussion at the international conference. During the discussion, the well-known cosmophysicist Thomas Gold hypothesized the existence of specific "solar whistlers", which are excited in solar flares and propagate along IMF lines just as whistling atmospherics are excited by lightning strokes and propagate along geomagnetic field lines.

The task set before us was interesting, but it proved to be extremely difficult. Proceeding from general ideas about the configuration of the magnetosphere and probable ways of wave penetration from the interplanetary medium into the magnetosphere, we began our search with a careful analysis of ULF oscillations in polar caps. This opportunity arose due to the fact that during the International Geophysical Year (1957–1958) under the guidance of prof. V.A. Troitskaya ULF oscillations were recorded at stations located in various regions of Earth, including Arctic and Antarctic [Troitskaya, 1961]. In this, Valeria Troitskaya's outstanding managerial talent manifested itself.

Soon after beginning the search for an answer to the question posed by V.A. Troitskaya, we discovered a previously unknown type of Pc1–2 (0.1–5 Hz) oscillations at the Vostok station in Antarctica [Guglielmi, Dovbnya, 1974]. It was proposed to call these oscillations *serpentine emission* (SE) because the dynamic spectrum of oscillations is remotely similar to a sliding snake (Figure 1). An unusual property of SE indirectly indicating its extramagnetospheric origin is that oscillations undergo deep frequency modulation. An important feature of SE is that oscillations can be observed under extremely quiet geomagnetic conditions: the typical geomagnetic index K_p=1 (SE morphology is described

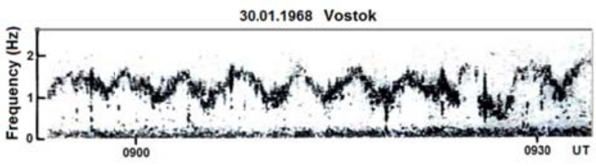

Figure 1. Dynamic spectrum of Pc1 oscillations with deep modulation of the carrier frequency [Guglielmi et al., 2015]

in more detail in [Troitskaya, 1979; Fraser-Smith, 1982; Asheim, 1983; Morris, Cole, 1986, 1987]).Guglielmi et al. [2015] argue that SE oscillations always exist in the solar wind, where they are self-excited due to the ion-cyclotron plasma instability, whereas the frequency modulation of SE occurs under the influence of Alfvén waves emitted by the Sun. Curiously, the characteristic period of the SE frequency modulation lasts five minutes (see, e.g., Figure 1). It coincides with the characteristic period of solar surface oscillations derived from helioseismology data [Ulrich, 1970]. A question arises as to whether we managed to find traces of oscillations of the red-hot solar surface in the icefields of Antarctica. We are sure that Valeria Troitskaya would like this idea.

So, if we adopt the viewpoint put forward in [Guglielmi et al., 2015], then SE is an ion cyclotron wave modulated in frequency by an Alfvén wave of solar origin. We tried to detect the modulating wave, using data on ULF oscillations. Taking into account the SE properties, we searched for a rare type of Pc5 oscillations that would have been observed under very quiet geomagnetic conditions (recall that Pc5 usually occur during geomagnetic storms). The preliminary result of the search is encouraging. A suitable candidate proved to be the so-called *big magnetic pulses* (BMP), which sporadically emerge at high latitudes under quiet magnetic conditions as isolated large-amplitude magnetic pulses. For a brief description of the BMP morphology, see, for example, [Zotov et al., 2013] and references therein. Figure 2 gives insight into BMP. The oscillations were recorded in the Antarctic observatory Mirny. Let us pay attention to two circumstances important for us. First, powerful ULF oscillations are observed at very low geomagnetic activity, and, second, the period of oscillations is close to five minutes.

The GO Borok has the richest archive of ULF oscillations, which were recorded at the observatory Mirny during Antarctic expeditions organized by V.A. Troitskaya. We are grateful to B.I. Klain for the kind permission to use BMP data from this archive. The preliminary result of processing of data accumulated from 1988 to 1995 is shown in Figure 3. We can see a fairly compact distribution of BMP over periods. In half of the events, the period of oscillations varied from 4 to 5.4 min. The average period is 4.8 min., i.e., it is quite close to the period of oscillations in the solar photosphere.

It is still difficult to say whether we managed to detect Alfvén waves excited on the Sun. However, there is one encouraging circumstance: Alfvén waves with a mean period of 4.75 min., genetically related to solar oscillations, have recently been discovered in the near-Earth interplanetary medium [Potapov et al., 2013].

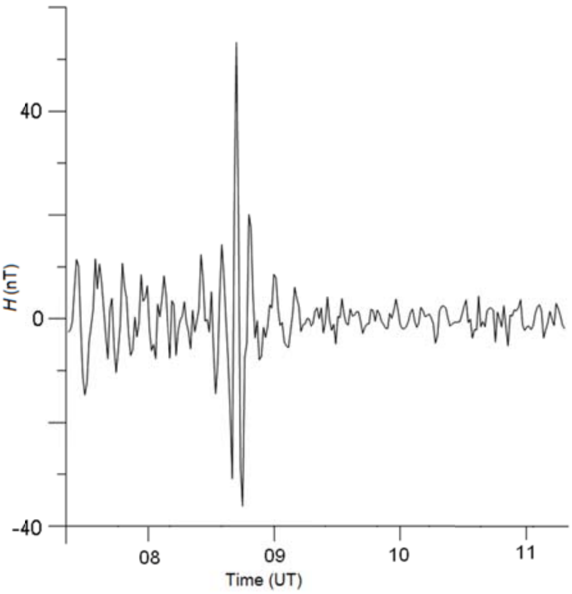

Figure 2. ULF oscillations in the Pc5 range recorded at the observatory Mirny on January 04, 1988 under fairly quiet geomagnetic conditions: K_p=1 [Zotov et al., 2013]

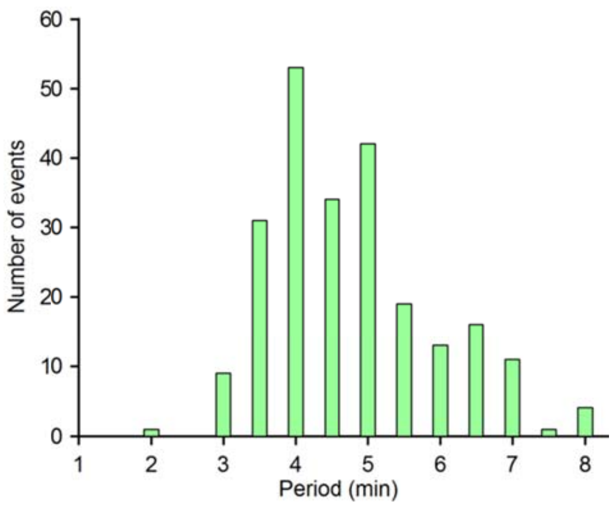

Figure 3. BMP distribution over oscillation periods

The scope of this paper does not allow us to describe the scientific achievements of Professor V.A. Troitskaya in any more detail. We focused only on one problem – the search for sources of ULF oscillations outside Earth's magnetosphere. Various aspects of this problem were of great interest to V.A. Troitskaya. This is a manifestation of her prophetic vision. And we are grateful to destiny that we were fortunate to begin this research under her leadership.

Valeria A. Troitskaya was an outstanding, amazing, and interesting person. Fascinated by science, a great hard worker, she was able to let everyone feel that his/her work is also interesting, useful and necessary. We remember the time we were still starting investigators, while she was already a famous professor. She enthusiastically discussed with us the special fascination of ultralow-frequency geoelectromagnetic oscillations. Could this fascination be associated with a special property of their space-time structure? Could these invisible and inaudible oscillations affect our subconsciousness as the rustle of foliage in a dense forest, ocean waves, or twinkling of stars do? Indeed, every living thing on Earth has experienced a small but constant influence of geoelectromagnetic oscillations for billions of years. Questions of this kind arise from time to time, and everyone may have a specific opinion on this matter, but no one has yet formed a convincing answer.

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