Victor Y. Trakhtengerts

(1939-2007)

Victor Trakhtengerts: His Contribution to Space Plasma Physics

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1. INTRODUCTION

The year 2014 marked the 75th anniversary of the birth of Victor Yurievich Trakhtengerts (1939–2007), who made an outstanding contribution to different areas of space plasma physics. The organizers of the 9th conference on the Physics of Plasmas in the Solar System dedicated an entire session to his memory, and this article is based on a presentation made at that session. The sections within this article correspond to the main areas of V.Yu. Trakhtengerts' (V.Yu.) research work.

The research interests of V.Yu. were shaped amid the rapid development of many fields of physics. He was part of the famous school of space plasma physics that was created in Nizhni Novgorod by V.L. Ginzburg and headed by V.V. Zheleznyakov. This school achieved its world-renowned results largely due to good neighborliness and creative interaction with other schools of thought that had grown from that of physics of nonlinear oscillations and waves at the Radiophysics Department of Gorky State University and were further developed at the Radiophysical Research Institute (RRI) and Institute of Applied Physics (IAP). Among these schools of thought, we note A.V. Gaponov-Grekhov's school of physical electronics and M.A. Miller's school of physics of nonlinear phenomena in plasmas. V.Yu. Trakhtengerts had creative fervour and a sense of discovery, which allowed him to go both deep and wide in his studies, exploring and creating new research fields and avenues. His outstanding personal as well as professional qualities allowed the scientist to educate many students and establish fruitful relations with many colleagues from different institutes and cities in our country and abroad. It is worth mentioning the great influence of V.Yu. Trakhtengerts on the studies of wave propagation in the near-Earth space conducted at the Polar Geophysical Institute in Apatity and the Institute of Space Physics and Aeronomy in Yakutsk. Trakhtengerts' renown in the world scientific community helped his informal scientific school to go through those troublesome times in the life of Russian science when researchers could do science and live in reasonable conditions only through the support of international foundations.

Of course, it would be impossible to give a full description of these research areas within one small article; the reader who wishes to explore the results described below in more detail is referred to the original and review works on selected topics that are given in the list of references. However, it seemed appropriate to bring together the main results obtained by our distinguished colleague and publish them in one text at least in the form of a brief enumeration. Here I should note that the level of detail in presenting the results depends to a large part on the competence of the author of this article.

2. SELF-CONSISTENT THEORY OF CYCLOTRON INSTABILITY

The questions of nonlinear resonant interaction of charged particles with waves in a plasma were the main subject of V.Yu. Trakhtengerts' research throughout his career. His pioneering works on this subject appear to be the most widely known. It is no coincidence that Victor Yurievich himself described these results in much detail in his reviews and books [1–5].

The first study in this area was [6], which focused on the linear theory of kinetic cyclotron instability in the Earth's radiation belts. In the 1960s researchers discovered unexpectedly powerful and long-lived sporadic emissions in near-Earth space in the whistler wave range (the frequencies of whistler waves $f \sim 1$–10 kHz belong to the so-called very low frequency (VLF) range), and vigorous efforts were made to explain this phenomenon. In particular, Brice [7, 8] and other researchers explored the mechanisms underlying the generation of discrete VLF signals, which are based on the coherent radiation of electron fluxes in the magnetosphere. Note that in the same years at Siple Station in Antarctica were conducted the widely known experiments that discovered triggered VLF emissions. V.Yu. Trakhtengerts was the first to propose an explanation for the high level of quasi-stationary sporadic noise emissions that were observed over tens of minutes and hours.

It is worth recalling that the first researchers to consider kinetic cyclotron instability caused by the anisotropy of the velocity distribution of charged particles were R.Z. Sagdeev and V.D. Shafranov [9]. Their study was preceded by the pioneering works of Gaponov and Zheleznyakov on the hydrodynamic instability of charged particle beams [10, 11].

A logical continuation of the first work was a generalization of the quasi-linear theory proposed by Vedenov, Velikhov, and Sagdeev [12] to the case of a magnetized plasma [13]. Subsequently, the quasi-linear theory formed the basis for the theory of the stationary state of radiation belts, which was published in the famous papers by Kennel and Petschek [14] and by Trakhtengerts [15].

The next stage in studying the dynamics of the cyclotron instability (CI) of radiation belts is associated with understanding the formation of nonstationary VLF signals. These signals had already been known at that time, in particular, from the works by Helliwell [16], but theoretical studies were initiated some time later. One of the first such works was the paper by Coroniti and Kennel [17] on the modulation of the CI growth rate by hydromagnetic waves.

Bespalov and Trakhtengerts [18] appear to have been the first to demonstrate the presence of relaxation (damped) oscillations about the steady state of radiation belts due to a dynamic equilibrium between the supply of energetic particles and their loss into the loss cone during their pitch-angle diffusion on waves they excited. A similar result was later obtained independently by Davidson [19]. The quality factor of these oscillations increases with decreasing power of the source of energetic particles and can be quite large, which enables effective resonant excitation of these oscillations by external sources such as hydromagnetic flux tube oscillations.

The next step in this direction was the discovery of a self-modulation instability in the interaction of CI with hydromagnetic oscillations, i.e., the mutual excitation of whistler waves and geomagnetic flux tube oscillations. In [20] this instability was found for the fast magnetosonic mode, and in [21] it was obtained for the Alfvén mode. Here it is worth mentioning the contribution of Mikhailovskii and Pokhotelov [22], who were the first to study the "direct" CI intensification process in the presence of hydromagnetic turbulence, without considering the feedback effect of CI on hydromagnetic waves.

An important milestone in the development of CI theory was the work by P.A. Bespalov [23], who was the first to consider the self-oscillating instability mode in the presence of a permanent source of energetic particles. This possibility was demonstrated in the framework of the approximation of a weak pitch-angle diffusion (with an almost empty loss cone) and unchanging shape of the wave spectrum. Under conditions existing in the Earth's magnetosphere, these modes correspond to oscillations of the wave intensity and fluxes of precipitating energetic particles, which have rather long periods (several tens of seconds in the case of whistler waves). V.Yu. Trakhtengerts and his colleagues from the Polar Geophysical Institute proposed a model of a flow cyclotron maser [24]. Abandoning the above approximations, this model was able to also explain the shorter periods of the self-oscillating mode (10–30 s), which correspond to the observed periods of pulsating auroral patches. Subsequently, this work was developed both in terms of numerical simulations and comparisons with observational data [25, 26].

In fact, the above works set the foundations of the theory of magnetospheric cyclotron masers (MCMs) whereby the MCM active substance is energetic charged particles with a nonequilibrium velocity distribution and the electrodynamic system for whistler and ion cyclotron waves propagating at small angles to the magnetic field is formed by geomagnetic flux tubes filled with a fairly dense ($\omega_{pe} > \omega_{Be}$, where ω_{pe} and ω_{Be} are plasma and cyclotron frequencies of electrons) cold plasma and by the regions of reflection of waves from the ionosphere. Another type of magnetospheric maser is the generators of auroral kilometric radiation and similar systems in the magnetospheres of other planets, which operate in a rarefied plasma ($\omega_{pe} \ll \omega_{Be}$). The latter systems are a cosmic analogue of gyrotrons because they enable the excitement of waves with a quasi-transverse direction of propagation with respect to the magnetic field.

The MCM theory used the results achieved both in the physics of quantum generators and in vacuum microwave electronics. In turn, the MCM theory allowed researchers to come up with several ways of using background plasmas in laboratory generators (cyclotron resonance maser with a background plasma [27]). So far these ideas have found application in interpreting [28] a series of experiments with laboratory magnetic traps, which demonstrated the pulsed generation of microwave radiation in a plasma containing, as in space conditions, a portion of energetic electrons with an anisotropic velocity distribution. Recently, there has been some interest in such experiments in the context of comparing laboratory results with space-based observations to better understand the physics of the processes involved. These works revealed new effects, e.g., relaxation oscillations of CI in a decaying plasma (i.e., in the absence of a particle source) [29, 30]. In this case an effective source is provided by the decrease of the collisional damping of waves during the decay of the background plasma [31].

The nonlinearity of the collisional damping of waves in a plasma (the damping decreases during the heating of the plasma by emerging radiation), which was suggested for the laboratory conditions as a model of how absorption saturation occurs in the cyclotron maser, has also found application for space conditions: such a situation may take place in solar coronal loops. As shown in [32], under the conditions of the solar corona, CI can develop in a relatively small area at the top of the flare loop. The CI area expands along the loop due to the heating of the neighboring colder areas by the generated waves to form a “heat wave.” It is important that energetic particles from the entire loop get involved into the instability process. The observational manifestations of CI (X-ray radiation from the edges of the loops due to precipitating energetic particles and the heating the central part of the loop) correspond to the manifestations of a solar flare.

Special mention should be made of the results obtained by V.Yu. Trakhtengerts and his colleagues in the study of the spatial structure of trapped and precipitating energetic charged particles, which is formed during their interaction with waves. For example, in [33] they proposed a theory of gap formation in the electron component of a radiation belt, which took into account the diffusion of particles in L-shells. Localized precipitations of energetic electrons in the duskside sector (at around the plasmasphere bulge) were found in [34] and analyzed in [35]. A general quasi-linear theory was built for the interaction of whistler waves with electrons, which took into account the mode structure of the electromagnetic field in a plasma waveguide [36].

This research field also includes studies on the dynamics of the partial ring current in the interaction with ion cyclotron waves. It appears that this issue was first raised by Cornwall et al. [37, 38]. Trakhtengerts showed [39, 40] that the localized nature of the precipitations of energetic protons into the ionosphere leads to the formation of sufficiently intense local current systems whose properties are consistent with those of the so-called subauroral polarization streams (SAPSs) [41]. The key point here is the consideration of the effect of the increased Hall conductivity in the ring current region of the magnetosphere on the formation of a magnetosphere–ionosphere current system. The increased conductivity leads to the concentration of ionospheric loop-closing currents and the corresponding polarization electric fields in a region that is conjugate with the partial ring current. Thus, the polarization streams were found to be an analogue of the substorm polarization jets at auroral latitudes discovered by Yu.I. Galperin et al. [42] (in the latter case, the concentration of the ionospheric closing current is due to an increased Pedersen conductivity of the ionosphere in the auroral precipitation region). Also noteworthy is a series of works written in collaboration with A. Grafe that are focused on the connection between the asymmetric part of low-latitude magnetic disturbances during magnetic storms and collective processes in the ring current [43–45].

The cyclotron maser topic was developed in the theory of generation of discrete signals in the magnetosphere, such as chorus VLF emissions. The works [46–49] proposed and developed a model of a magnetospheric backward wave-oscillator (BWO), which was able to explain such important properties of chorus signals as the high growth rate, the lesser length of the generation region along the magnetic field line, and fast frequency drift and assess the characteristic wave amplitudes. The backward-wave oscillator (or more precisely, gyro-BWO) mode is an absolute instability, which develops in the absence of wave reflections given a sufficiently deep feedback relationship between the electromagnetic wave and space charge (or resonance current) wave. Under magnetospheric conditions, CI can make a transition to the BWO mode where there is a rather sharp drop (step) in the function of the electron velocity distribution, and this drop (step) forms naturally in the cyclotron interaction with noise emissions [50].

It was shown in [51] that the BWO regime may also exist for ion cyclotron waves where there are the so-called hydromagnetic chorus.

The frequency drift that is commonly observed in chorus emissions is a typical feature of discrete signals under natural conditions. In [52] the results for the trapping and acceleration of particles by the quasi-monochromatic wave field were generalized to the case of a wave packet with varying frequency, paying attention to the special case of a whistler generated by a lightning discharge. Here it was shown that, during a single passage of the wave packet in the conditions of the Earth’s magnetosphere, an electron trapped by the wave field can gain an energy of a few tens of keV, with this process bearing a nondiffusive nature, and the sign of the energy exchange depending on the sign of the frequency drift. This work was the first in a stream of papers published by different authors since it gave evidence for an effective mechanism of electron acceleration in the radiation belts. In [53] this result was generalized to the relativistic case to show that the nondiffusive acceleration conditions are satisfied in the case of chorus VLF emissions for electrons in the tail of the distribution function (this is due to the dependence of the frequency drift rate, which determines the trapping conditions, both on the signal amplitude and the particle energy found in [47, 48]).

It seems appropriate to end this section by mentioning the Resonance project aimed at studying wave phenomena in the inner magnetosphere, which was the proposed by V.Yu. Trakhtengerts together with colleagues from the Space Research Institute [54, 55].

The distinctive feature of the project is the magnetosynchronous orbits of the satellites (two pairs in the current scheme), which are to stay for up to 1–3 h within one magnetic flux tube with lateral dimensions of about 100 km at the level of the ionosphere. Unfortunately, project implementation is being delayed and, in fact, seems to be questionable; however, the problems set within the project are still relevant.

3. NONLINEAR EFFECTS DUE TO HF HEATING OF THE IONOSPHERE

In the 1970s–1980s, a major subject in V.Yu. Trakhtengerts' research work was, over several years, nonlinear phenomena in the ionospheric plasma under the effect of a powerful HF radiation. These experiments facilitated the rapid development of the physics of nonlinear phenomena in a plasma; one of the first theoretical studies on this subject was a paper on the stimulated scattering of waves in a magnetized plasma [56].

V.Yu. Trakhtengerts took an active part in the theoretical interpretation and planning of many of the early experiments on HF heating of the ionosphere. Here noteworthy are two of his theoretical results in this area. One of them is the creation of the linear and nonlinear theory of thermal parametric instability (TPI) in the ionospheric plasma. This instability develops more slowly than the striction instability in the plasma resonance region, but has a much lower threshold for the pump wave intensity and, most importantly, leads to the formation of small-scale plasma irregularities in the upper hybrid resonance region, which is located in the ionosphere below the plasma resonance. For this reason, in the typical conditions, the absorption of the pump wave from a ground-based transmitter by the upper-hybrid turbulence shields the upper lying region of the plasma resonance. The most detailed account of the TPI theory can be found in [57]. Note that the version of hard excitation of TPI in the presence of already existing plasma irregularities was developed by V.V. Vas'kov and A.V. Gurevich [58].

The second fundamental result obtained by V.Yu. Trakhtengerts on nonlinear effects in the ionosphere is the theory of generation of signals in the ionosphere at combination frequencies (the Getmantsev effect) [59, 60]. In recent years, this subject has become popular again in connection with the ideas related to active influence on the Earth's radiation belts. Also, it is worth mentioning the work on the excitation of oscillations in a neutral atmosphere (internal gravity waves) by HF heating [61].

The personal experience of the research participants and some of the scientific details were published in a collection of papers dedicated to the memory of V.Yu. Trakhtengerts, which was compiled by N.A. Mityakov and E.E. Mityakova.

4. IONOSPHERIC ALFVÉN RESONATOR

V.Yu. Trakhtengerts' scientific authority opened the doors for studies on the ionospheric Alfvén resonator (IAR) [62, 63]. Although the manifestations of the resonance properties of the ionosphere accompanying the reflection of Alfvén waves had, in a sense, already been known from the works by Greifinger [64, 65] and the concept of the resonator had been formulated by S.V. Polyakov [66], it was V.Yu. Trakhtengerts who promoted strongly to the experimental studies that discovered IAR manifestations in the resonance spectral structure (RSS) of the electromagnetic background noise in the atmosphere in the frequency range 0.5–10 Hz [67]. V.Yu. Trakhtengerts was also involved in the development of the RSS theory [68].

In collaboration with A.Ya. Fel'dshtein, V.Yu. Trakhtengerts discovered the instability of magnetospheric convection, which leads to a buildup of Alfvén waves in the IAR [69, 70]. The vertical scale of these disturbances ($l_{\|} \sim 500$ km) is much larger than the horizontal one ($l_{\perp} \sim 1$–10 km); i.e., they are Alfvén vortices elongated along the magnetic field, and these scales are consistent with the observed scale of the fine structure of field-aligned currents in the auroral zone. Subsequent studies [71–74] considered the nonlinear stage in the evolution of these vortices, during which a current instability and anomalous resistivity develop in the upper ionosphere. As a result, a longitudinal electric field emerges, and a part of the electrons is accelerated in the runaway regime and precipitates into the lower ionosphere, altering the ionization balance and, thereby, amplifying the initial instability of the Alfvén waves. These processes allow researchers to explain many of the characteristics of the auroral westward travelling surge, which is a typical manifestation of an auroral substorm. The nonlinear instability regime in the IAR has much in common with the ionospheric feedback instability (IFI), which was proposed in [75]; however, the consideration of the resonator properties of the ionosphere leads to a model whereby the excited structures have smaller latitudinal dimensions and, in fact, are embedded in larger-scale structures formed during the development of the IFI.

In [76, 77], schemes were proposed for active experiments on the stimulation of the instability of auroral Alfvén vortices by the periodic heating of the ionosphere. This problem is still relevant, although there has not been any visible progress in the experimental realization of this approach, except, perhaps, in [78]. The failure of the experiments is partly due to the neglect of the synchronism between the transverse structure of the currents excited by HF heating and IAR eigenmodes (see, e.g., [79]).

According to [80–82], the IAR effects should be manifested in wave spectra in the Pc1 frequency range (0.1–10 Hz), which are generated in the magnetosphere by energetic protons due to cyclotron instability.

Victor Trakhtengerts in Web of Science (since 1980)

Subject	Reference	Number of citations according to WoS
Chorus generation	[47]	95
Ionospheric Alfvén resonator	[63]	71
Turbulent boundary layer in the ionosphere	[74]	68
BWO regime for chorus generation	[46]	63
Relationship of noise and discrete emissions	[50]	43
Cluster data on chorus emissions and BWO regime	[48]	39
Pulsating auroral patches	[25]	34
Flow cyclotron maser and pulsed VLF emissions	[24]	26
Precipitations of ring current protons and Pc1 and IPDP pulsations	[97]	25
IAR role in the origin of Pc1 pulsations	[98]	25
SEE of the ionosphere in two-frequency heating	[99]	23
Numerical modeling of chorus emissions	[100]	22
Cyclotron acceleration by whistlers	[52]	22
Alfvén sweep maser	[82]	22
Review on interaction of whistler waves with electrons	[3]	21
Excitation of Alfvén waves in HF heating of ionosphere	[77]	21
Resonant structure of low-frequency noise spectrum: observations	[101]	20
Resonant structure of low-frequency noise spectrum: theory	[68]	19
Triggered emissions and power-line harmonics	[102]	19
Change in the spectrum of chorus emissions in the generation region	[49]	18

For waves in this range that extend downward from the magnetosphere, the IAR serves as a selective mirror, the reflection coefficient of which is resonantly dependent on frequency (as in the case of the Fabry—Perot cavity) and, moreover, can change due to a change in the ionospheric parameters under the influence of precipitating energetic protons. Thus, there is magnetosphere—ionosphere feedback, due to which the ion cyclotron wave generation is characterized by the presence of passive-mode locking (this magnetospheric phenomenon was first considered by P.A. Bespalov for whistler waves with the use of a different nonlinearity [83]). This nonlinearity leads to the formation in the system of a stable packet of Alfvén waves with a frequency drift (Alfvén sweep maser), which oscillates between conjugate regions of the ionosphere. The properties of this solution are largely consistent with the so-called Pc1 pearls [84, 85]. Note that the discussion about the nature of the pearls is still ongoing [86, 87].

5. COLLECTIVE EFFECTS IN ATMOSPHERIC ELECTRICITY

At the end of the 1980s, Trakhtengerts' sphere of interests expanded to include the problems of atmospheric electricity. He published the world's first work on dust-acoustic wave [88], where he considered the dissipative instability of a flow of charged macro-particles in an aerosol plasma in the context of thunderclouds (the term dust-acoustic mode was coined later). Subsequently, this study was used to propose a model of how anomalously large radio reflections develop in the polar mesosphere (polar mesospheric summer echoes) [89]. In [90, 91], this instability was proposed to explain the formation of structures such as dust crystals. Another instability, based on variations in the charge of large particles in induction charging, was considered in [92].

Flow instability in a dusty plasma was subsequently used as an elementary process in the generation of local superbreakdown fields in a thundercloud, and this idea developed into the "fractal" direction in V.Yu. Trakhtengerts' works written in collaboration with D.I. Iudin. In [93—95], a mechanism was proposed for the fractal activation of a lightning discharge at a preliminary stage under the conditions whereby the average field in a cloud is visibly lower than the breakdown field. Local breakdowns generated by electric fields due to instability form a percolation cluster over which the discharge current can be pulled into a narrow channel from a large part of the cloud. Interestingly, the fractal processes are largely independent of the physical processes and interactions in the unit cell (in a thundercloud this may be, e.g., runaway breakdown [96]); i.e., this scenario is universal in nature.

6. CONCLUSIONS

Some of the works by V.Yu. Trakhtengerts were not included in this review because of length limitations. These are, in particular, works on the generation of lower hybrid waves in the polar ionosphere, the properties of internal gravity waves in the atmosphere and their relation to ozone perturbations, radio acoustic sounding of the atmosphere, acceleration of charged particles in the current sheet, etc.

In conclusion, I would like to discuss the scientometric viewpoint on V.Yu. Trakhtengerts' contribution to science. The Web of Science (WoS) database gives information on his publications since 1980, listing 133 items. The official list of publications for all years, which was compiled by Victor Yurievich himself, contains more than 250 works.

The table presents the publications with the highest number of citations according to WoS.

It can be seen from this list that, in general, the greatest recognition was received for the works that are part of the most extensive series of papers written by V.Yu. Trakhtengerts, which are dedicated to cyclotron interaction in the magnetosphere (in the first place, the origin of chorus and quasi-periodic VLF emissions), phenomena associated with the ionospheric Alfvén resonator, and active experiments in HF heating of the ionosphere. The first and last of these series may also include other papers, which are not registered in the public WoS database because they were written before 1980. In my opinion, a number of works, in particular, those on atmospheric electricity, laboratory applications of the cyclotron instability theory, and the acceleration of particles in the resonant interaction with waves have yet to find their reader. Of course, the works that are already widely cited in the literature are far from having exhausted the potential of their impact on research in space plasma physics. It is hoped that V.Yu. Trakhtengerts' ideas on dynamic regimes in the development of instabilities in open plasma–wave systems, the relationship between noise and discrete signals generated in a nonequilibrium plasma, turbulent Alfvén boundary layers in the dynamo regions of planetary magnetospheres, and dissipative flow instabilities in a dusty plasma will find application both in the analysis of new data on the near-Earth space and in the study of other astrophysical objects and in laboratory experiments.

Apart from the purely scientific heritage, at least two generations of researchers will feel the impact of V.Yu. Trakhtengerts' outstanding personality and his noble attitude to scientific creativity and to his colleagues. In the last three and a half years of his life, he had to contend with a serious illness, but he continued to work actively and was able, to a large extent, to prevent his illness from affecting his relations with colleagues and friends. These topics are covered in detail in the above-mentioned book dedicated to the memory of Trakhtengerts, an expanded edition of which is now being prepared at the IAP RAS.

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