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In memory of Vladimir Evgen'evich Zakharov

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The outstanding Soviet and Russian scientist and academician of the Russian Academy of Sciences (RAS), Vladimir Evgen'evich Zakharov, suddenly passed away on August 20, 2023.

V E Zakharov (VE) was one of the founders of modern nonlinear physics and mathematics. His achievements in these areas have long been classical and recognized by the scientific community throughout the entire world. His pioneering work became the foundation of at least three key areas of nonlinear physics: wave turbulence, solitons, and wave collapses. VE's work in the listed areas covered almost all fields of modern theoretical physics, including plasma theory, hydrodynamics, solid-state physics, nonlinear optics, geophysics, gravitational theory, and field theory.

V E Zakharov was one of the authors of the inverse scattering transform in the theory of integrable systems, which was him the recognition of not only theoretical physicists but also mathematicians. According to L D Faddeev, this method became the pearl of mathematical physics in the twentieth century. VE was a pioneer in this area of mathematical physics, and his enormous contribution is difficult to fully appreciate.

VE was born on August 1, 1939 in Kazan into an educated family of Zakharovs: Evgenii Semenovich, an engineer by profession, and Elena Mikhailovna, a biology teacher at a secondary school. His father was a veteran of the Great Patriotic War. Volodya Zakharov went to school in Kazan and finished school in 1956 in Smolensk, where his family had moved. When a 7th–8th-year schoolboy, he became interested in mathematics and was a winner of the school Olympiads. After school, three years of study at Moscow Power Engineering Institute (from 1956 to 1960), and one year of work at the I V Kurchatov Institute of Atomic Energy as a laboratory assistant in G I Budker's department, he moved to Novosibirsk together with the Institute of Nuclear Physics (INP) being organized. This was where his work in science began.

In 1963, VE graduated with honors from the Physics Department of Novosibirsk State University (NSU). This was the first famous graduate of Novosibirsk University. In 1962, the *Journal of Experimental and Theoretical Physics* (*ZhETF — JETP*) published the first scientific paper of V E Zakharov, then only a student, (jointly with V I Karpman) about nonlinear plasma wave damping, which became classical in this field. After graduation from NSU, nonlinear physics became the main area of his research.

In 1963, VE began working in INP of the Siberian Branch of the USSR Academy of Sciences, where he defended his PhD thesis under the guidance of R Z Sagdeev in 1966 and his doctoral (the second scientific degree in the Soviet Union) thesis in 1971. The results of his PhD thesis exceeded in quality many doctoral theses. In particular, V E Zakharov formulated the variational principle and found canonical variables to describe waves on the surface of water. Later, for his pioneering work on the Hamiltonian wave theory in hydrodynamics with a free surface, he was awarded the N N Bogolyubov Gold Medal of RAS. On the basis of a Hamiltonian description (the Zakharov equations), another fundamental result was obtained, namely, scale-invariant spectra of wave turbulent seas were found as exact solutions of the Kolmogorov type of the wave kinetic equations describing energy transfer over scales. Such spectra are due to nonlinear wave interaction and in no way are close to thermodynamically equilibrium ones. They were called Kolmogorov-Zakharov spectra. Along with direct wave energy transfer to the short-wave region, where viscous damping is noticeable, Zakharov predicted for water waves the existence of an inverse cascade, when, owing to a nonlinear interaction, waves are transferred to a long-wave region. This was a monumental achievement. For this discovery, Zakharov, together with Robert Kraichnan, received the 2003 Dirac Medal. It immediately became clear that wave turbulence, as the state of a random wave field, is typical not only of turbulent wave seas, but also of various

Vladimir Evgen'evich Zakharov
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waves in plasma, in a solid, acoustics, nonlinear optics, and geophysics.

To describe nonlinear waves in various media, Zakharov sequentially and persistently introduced a Hamiltonian formalism. This made it possible to consider from a unified standpoint all the nonlinear wave phenomena traditionally thought of as unrelated to each other.

Two of VE's outstanding papers are also from the Novosibirsk period. The first was the prediction of Langmuir wave collapse in plasma (1972) that is a spontaneous increase in the electric field intensity of Langmuir oscillations in the region of lowered plasma density. The Langmuir wave collapse, as a nonlinear stage in the development of modulation instability, leads to Langmuir packet compression to sizes of several Debye radii. This process is accompanied by the generation of fast electrons with an energy considerably exceeding the thermal energy. The Langmuir collapse theory is based on the averaging method that allowed deriving equations for the interaction of Langmuir and ion oscillations in plasma, which are now called the Zakharov equations. This work by VE radically changed the understanding of plasma turbulence and the dissipation mechanisms of high-frequency wave turbulence in collective methods of plasma heating. The work on Langmuir collapse produced a noticeable impact on the development of nonlinear research not only in plasma physics but also in nonlinear optics and hydrophysics.

Another very important result was the epochal work of 1971 by Zakharov and Shabat on the integration of the nonlinear Schrödinger equation (NLSE) by the inverse scattering transform (IST). As a canonical model of nonlinear wave physics, the NLSE has a huge number of applications, beginning with ocean waves, plasma, and acoustics to Bose–Einstein condensates, including self-focusing, fiber optics, and high-speed optical communication. Such generality is due to the fact that the NLSE describes the nonlinear dynamics of envelopes in a weakly nonlinear regime; it can be obtained for arbitrary nonlinear media using the Hamiltonian formalism. The mathematical basis of this work is related to the solution to the inverse problem for a linear operator — the Zakharov–Shabat operator, whose spectrum remains time independent. Solitons are defined by the position of the discrete spectrum of a given operator. The most interesting physical consequence of the Zakharov–Shabat study was the establishment of the role of solitons as particle-like objects. Solitons in the NLSE turned out to be structurally stable, which allowed their use as information bits in fiber-optic communications. The breakthrough article by Zakharov and Shabat became a trigger for numerous studies on the application of the IST to various physical models. Moreover, it has led to the development of new mathematical methods, including the application of algebraic geometry and the theory of matrix differential operators. A whole new field arose — the mathematical theory of solitons — and VE himself made a significant contribution to it.

In 1974, VE moved to Chernogolovka, where until 2003 he worked at the L D Landau Institute for Theoretical Physics (ITP). From 1993 to 2003, he was director of the ITP. Here, he continued his active scientific work on wave turbulence, soliton theory, and wave collapses. The creation of the wave collapse theory, beginning with VE's studies on Langmuir collapse and light self-focusing up to the investigation of interactions of collapses with weak wave turbulence, as well as the effect of plasma collapses on particle spectra, were his fundamental contributions to the physics of nonlinear phenomena. The very term 'wave collapse' was introduced in VE's work and is now widely used in the scientific community. According to the conception formulated by VE and his disciples, the physical realization of wave collapse or solitons depends on the boundedness or unboundedness of the wave system Hamiltonian. The case of a bounded Hamiltonian made it possible to discover stable solitons, whereas unboundedness became one of the criteria of wave collapse.

A significant contribution to the theory of wave turbulence was made by his joint studies with colleagues (V S L'vov, S S Starobinets, and others) on the so-called S theory, describing the above-threshold behavior of waves upon their parametric excitation by a coherent source (1971–1975). The basis of this theory is related to a simultaneous consideration of both normal and anomalous pair correlators. In a sense, this theory turned out to be analogous to the BCS theory for superconductivity. The main prediction of the theory is the existence of singular turbulence spectra, confirmed in experiments on spin wave parametric excitation in ferromagnets. The development of these studies by VE and his students for plasma physics has led to the discovery of singular turbulence spectra upon induced wave scattering — distributions in the form of points or jets in k space.

Zakharov's purely mathematical results are also worthy of note. He solved the classical problem of the differential geometry of the description of all orthogonal coordinate systems in an n-dimensional space. This problem was formulated in the early 19th century and is related to the names of great mathematicians: Riemann, Bianchi, and others. Rather nontrivial and beautiful is the Zakharov–Shabat dressing method, allowing efficiently constructing soliton solutions for integrable systems. The development of such methods showed their efficiency in solving some physical problems of field theory, gravitation, nonlinear optics, and hydrodynamics. In 1978, VE, together with V A Belinsky, established the integrability of Einstein equations for two-dimensional metrics and obtained classification of their solutions by spectral methods with a variable spectral parameter. The simplest solution in the form of a black hole is an analogue of the soliton, frequently referred to as the Zakharov soliton. VE and his students made use of the IST to solve the classical problem of superfluorescence. They found asymptotical states — analogs of the precursor for stable media in the form of pulses propagating through an inversely populated two-level amplifying medium. A great influence on the development of the inverse scattering transform was exerted by VE's work of 1981 on the integration of Benni's equations as a multidimensional hydrodynamic-type system.

In 1984, V E Zakharov was elected a corresponding member of the USSR Academy of Sciences in the Division of General Physics and Astronomy, and, in 1991, a full member of RAS. Beginning in 1992, VE taught at the University of Arizona (Tucson, Arizona, USA), where in 2004 he was awarded the honorary title Regent's Professor of the Board of University Governors. In 2012, he was elected to the European Academy of Sciences, to the rank of Fellow in the American Mathematical Society and the Optical Society of America. From 2004 to 2019, he was the head of the Mathematical Physics Sector at P N Lebedev Physical Institute. In 2010, VE returned to his alma mater (NSU) to head the Laboratory of Nonlinear Wave Processes in the framework of the 1st wave of megagrants. In 2019–2022, he headed the Laboratory of Integrable Systems at the Skolkovo Institute of Science and Technology. In 1988, he became a permanent chair of the RAS Scientific Council on Nonlinear Dynamics.

In recent years, Vladimir Evgen'evich had been actively involved in two of the most important problems. He formulated one of them as integrable turbulence, that is, turbulence in integrable models, in particular, in the nonlinear Schrödinger equation. The second problem relates to rogue waves in turbulent wave seas. Rogue waves are large-amplitude phantom waves arising from nowhere and then vanishing. They are very dangerous for shipping and offshore oil platforms. The rogue-wave research started by VE is now being rapidly developed, providing practical predictions of risks for navigation and also for modern fiber optics communications.

Throughout his entire scientific career, VE actively developed the theory of wind driven waves in the ocean. He is a recognized founder of this field. For services in this field, he was elected in 2018 to the American Geographic Union (AGU) to the honorary rank of Fellow.

In our opinion, the main thing in Zakharov's scientific biography is that he obtained outstanding results in all areas of nonlinear physics and mathematics. For his scientific activity, he received two state prizes: the 1987 USSR Prize for work on nonlinear plasma physics and the 1993 RF Prize for the development of the theory of integrable systems.

VE's scientific activity cannot be imagined without his school, which he began to organize already in Novosibirsk. His first students were not much younger than their teacher, but, remaining the leader, he was always on friendly terms with his students, and later with students of his students. The atmosphere at the school was democratic. This is now a large school of talented scientists, known in the world scientific community as the Zakharov school.

Zakharov was an idol to several generations of scientists. The reason was not only his outstanding scientific results but also his public stand in respect of many events taking place in the country and particularly around science.

He first expressed his public stand in Novosibirsk, signing a letter in defense of freedom for Daniel and Sinyavsky. Another example from Soviet times is his letter to the Lenin Prize Committee demanding the reinstatement of A B Shabat, excluded from the list of nominees (together with Zakharov and Faddeev) for non-political reasons. Honesty and aversion to compromise on fundamental issues were some of VE's traits.

In post-Soviet times, especially in the 1990s, he, together with V E Fortov and others, fought for Russian fundamental science, demonstrating his broad 'state' view of a patriot on its development. He took the initiative to organize scholarships for outstanding Russian scientists and support leading scientific schools. This was very important in the 1990s. Together with E P Kruglyakov, E B Aleksandrov, and many others, VE devoted great effort to fight against pseudoscience, which saved enormous public funds from fraudulent projects. Zakharov spoke out categorically against the 2013 reform of the Russian Academy of Sciences He was one of the organizers of the First of July club of leading Russian scientists who opposed the reform. This club, in which VE was one of the informal leaders, continues its creative activity on issues of the organization of science for the revival of Russian science. His speeches in defense of science at general meetings of the RAS were always accompanied by applause. Many people considered him to be the voice of conscience at the Russian Academy of Sciences.

His scientific talent together with his human qualities and the scale of his personality gained tremendous authority and attracted many people to him, which was also facilitated by his poetry. As a poet, VE received the highest praise from professional poets and writers. This hypostasis of VE's was a continuation of his scientific creativity. The scale of his poetic gift can be judged by the six-volume edition of his poetry issued rather recently. Some of his poems were included in the anthology of Russian poetry of the 20th century edited by E A Evtushenko. VE was a member of the Union of Writers of Russia and the Union of Writers of the 21st century. He was a laureate of the Petropolis literature prize and the Victor Rozov Medal for his contribution to Russian culture. An asteroid (Asteroid 7153) was named Vladzakharov in honor of V E Zakharov.

The departure of Vladimir Evgen'evich Zakharov, a great scientist, citizen, and poet, is an irretrievable loss for all of us. The happy memory of him will live in our hearts.

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