

PERSONALIA

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Roald Zinnurovich Sagdeev (on his 90th birthday)

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December 26, 2022 is the 90th birthday of the outstanding physicist, pioneer of fusion and space research, academician of the Russian Academy of Sciences (RAS), Roald Zinnurovich Sagdeev.

R Z Sagdeev was born in Moscow, where at that time his father was studying. In 1937, the Sagdeev family moved to Kazan. After graduating from high school in 1950, RZ [1] entered the Physics Department of Moscow State University (MSU) and graduated in 1955. Already in his student years, he attracted the attention of L D Landau, who soon took a great interest in his future.

In those days, there was great demand for graduates of physics departments from nuclear weapons laboratories, and RZ was sent to do his graduate research at the leading one, Arzamas 16 and, after graduating from MSU, he went to the newly created center now known as Snezhinsk. This would seemingly predetermine his career; however, RZ saw his future in 'open' science and dreamed of working under the guidance of L D Landau.

RZ turned to Landau for help, and the latter approached I V Kurchatov, the highly influential head of the Soviet nuclear program. As a result of Kurchatov's efforts, the appointment to Snezhinsk was canceled, and RZ was sent to the Institute of Atomic Energy (IAE, now the Kurchatov Institute), which was situated in Moscow and called at the time the Laboratory of Measuring Instruments of the USSR Academy of Sciences. This decision allowed RZ to continue his regular participation in Landau's seminars, although he could not be officially enrolled in the postgraduate school of the Institute for Physical Problems (IPP), where Landau worked.

At IAE, Sagdeev joined the scientific group of M A Leontovich, engaged in the theory of hot plasma — a completely new state of matter with a large number of collective degrees of freedom, prone to excitation of numerous oscillation branches and transition to the regime of chaotic turbulent motions. Interest in this field of physics was associated with the idea of controlled thermonuclear fusion (CNF): to achieve the goal, it was necessary to reliably keep plasma in a magnetic field, but plasma (in those days) quickly escaped from magnetic traps. There was a point of view that plasma diffusion across the magnetic field follows the D Bohm model and for realistically achievable magnetic fields occurs so quickly that the implementation of CNF becomes impossible.

One of the first publications by RZ charted a path to understanding this problem. In the 1959 paper, he (together with L I Rudakov) showed that the plasma density and temperature gradients, which are inevitably present in any

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magnetic confinement scheme, cause the development of significant density and temperature fluctuations associated with the drift motion of particles; these fluctuations cause the anomalously large (or simply 'anomalous') diffusion of the plasma. This was a breakthrough in understanding the problems of plasma confinement. It also became clear that anomalous diffusion does not necessarily reach the Bohm level, so that magnetic confinement of the plasma had a chance of success. To date, a good understanding of the anomalous mechanisms of plasma diffusion has been achieved in tokamaks, stellarators, and other plasma confinement systems.

At the same time, RZ, as a result of his study of various forms of macroscopic plasma motions in a magnetic field, laid the foundations for two more scientific disciplines: the physics of solitary waves (solitons) and the physics of shock waves in a so-called 'collisionless' plasma, i.e., plasma with negligibly rare collisions between particles. In 1958, he established that nonlinear perturbations propagating across a magnetic field

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Translated by E A Kuznetsov and D D Ryutov

[1] As Roald Zinnurovich is often called in the circle of his students and friends; we follow this tradition.

can take the form of solitons and investigated their possible parameters. The research on the physics of solitons began to develop rapidly, and for more than half a century, solitons have been a subject of active research both in the field of applications and in the field of mathematical features of these structures, in particular, their connection with the inverse scattering transform.

At present, this is a scientific field of its own, widely represented in almost all areas of modern physics. A great and widely recognized contribution to the development of soliton physics has been made and continues to be made by RZ students.

Collisionless shock waves were discovered by R Z Sagdeev as a result of the analysis of the process of overturning Riemann solutions in plasma flows across a magnetic field. It turns out that, in the presence of wave dispersion in the plasma, the transition from the initial to the final state can occur in the form of damped oscillations, even in the case of very rare collisions. Another mechanism, especially effective in the case of strong shock waves, is associated with the development of turbulent electromagnetic fluctuations in interpenetrating flows in the overturning zone; the scattering of plasma particles by these fluctuations imitates dissipation at the front of a conventional collisional shock wave. The theoretical prediction of the existence of collisionless shock waves has led to an 'explosion' of research on such waves all over the world. In astrophysical journals, dozens of publications in which observed phenomena both in near and far space are explained with the help of collisionless shock waves appear each year. Experiments on the physics of collisionless shock waves are carried out with large pulsed lasers and many other facilities.

Work on nonlinear waves in a collisionless plasma served as the basis for a Candidate of Science thesis, defended by RZ in 1961 at IPP. During the defense, P L Kapitza made a playful remark that the applicant was a little hasty: if he had worked on the issues covered in the dissertation for three more months, the dissertation would have to be defended as a doctoral[2] one and there would be no need to convene the Dissertation Council again. Landau also made flattering remarks both about the work and about the applicant.

In the early 1960s, RZ, together with A A Vedenov and E P Velikhov, developed the quasi-linear theory of plasma. This model was the first step towards the development of a more complete theory, in which numerous branches of plasma oscillations were considered quasiparticles capable of decaying, merging, and scattering, as well as being emitted and absorbed by electrons and ions. This theory was called the theory of weakly turbulent plasma.

In 1961, RZ was invited by G I Budker to join the Institute of Nuclear Physics (INP, now named after G I Budker) of the newly created Siberian Branch of the Academy of Sciences in Novosibirsk. The RZ 'team' included his first students, A A Galeev, V E Zakharov, and A M Fridman, as well as G M Zaslavsky, V I Karpman, S S Moiseev, and V N Oraevsky. RZ shared his ideas widely. Everyone who closely collaborated with him remembers his ability to spark their interest in ideas that just occurred to him, and then help them at every step of the way of their further development. Not surprisingly, almost all of RZ's publications have co-authors. Moreover, according to the Soviet tradition of that time, the list of authors was alphabetical, and RZ was seldom the first author. The performance of Sagdeev's team at INP was astounding: it made widely recognized contributions to the physics of plasma turbulence, collisionless shock waves, transport processes in fusion devices, and other areas of plasma physics and hydrodynamics.

In 1963, RZ defended his doctoral dissertation at INP; the reviewers were Ya B Zeldovich, I E Tamm, and B V Voitsekhovsky. In 1964, he was elected a corresponding member of the USSR Academy of Sciences.

In the second half of the 1960s, the RZ group significantly advanced the theory of anomalous diffusion by discovering additional instability branches and means of their stabilization in some magnetic configurations (the latter — jointly with M N Rosenbluth and B Coppi). The application of the quasilinear theory made it possible to solve the important problem of the anomalously high electrical resistance of plasma.

In joint work with A A Galeev, new mechanisms of plasma diffusion in tokamaks and stellarators were pointed out, those associated with a specific banana-like shape of charged particle trajectories in these devices. In this case, the jump of a particle from one orbit to another occurs due to collisions between particles, as in classical gaseous diffusion. Hence the name of the new diffusion mechanism: neoclassical. Nowadays, this mechanism is necessarily taken into account when designing all new installations for controlled thermonuclear fusion.

Other important achievements of the group were, inter alia, the theory of the spectra of acoustic turbulence, the emergence of a chaotic magnetic field, and the properties of chaos in a turbulent medium.

R Z Sagdeev had a strong influence on the teaching of physics at Novosibirsk State University, whose first graduates still remember his lectures, his jokes, and his easy accessibility for the students.

In 1968, R Z Sagdeev was elected a full member of the USSR Academy of Sciences. At that time, his interests began to shift towards the physics of space plasma. At the beginning of 1971, RZ moved to Moscow, where in 1973 he was appointed director of the Space Research Institute (IKI) of the USSR Academy of Sciences. Such an appointment was a natural consequence of the understanding that arose at that time that plasma processes play a decisive role for many objects in the Universe.

RZ's fifteen years became the years of 'Sturm und Drang' in Soviet space exploration. Space research in the USSR (as well as in the USA) has always remained a closed field of activity, but, during these years, IKI became the world leader in international cooperation.

In the late 1970s, RZ stimulated active experiments in space (the Soviet-French ARAKS project). Effects caused by an electron beam from the French ARIAN rocket launched from Kerguelen Island in the southern hemisphere were recorded at a magnetically conjugated point in the Kostroma region.

In the early 1980s, RZ became the 'brain and heart' of the VEGA project. Two vehicles, VEGA-1 and VEGA-2, were to carry out *in situ* measurements of the properties of a comet in the solar system for the first time in history. Halley's comet was chosen as the subject of study. When carrying out a gravitational maneuver during a flyby of the planet Venus (hence the name of the project: Venus + Halley, in Russian

[2] In the Soviet Union, in addition to the Candidate of Science degree (identical to the PhD degree in the West), a higher, and much more prestigious, degree (called a Doctor of Science) existed.

transcription), two balloon probes were to be delivered into the atmosphere of this planet to register atmospheric processes, in particular, atmospheric circulation. The VEGA project became a true triumph of national science, at the same time opening up unique opportunities that international cooperation can provide: VEGA scientific equipment was created in broad international cooperation, and scientists from nine countries participated in 14 scientific experiments.

In the zone of the closest approach of VEGAs and the comet's nucleus, mass spectra of cometary plasma ions were obtained. The most unexpected event was the discovery of iron ions that were not observed in the optical spectra. The core itself turned out to be an elongated, irregularly shaped body with dimensions of about $15 \times 7 \times 7$ km. During the measurement period, Halley's comet was losing about 40 tons of water per second. Calculations have shown that this can happen only in the case of the evaporation of an ice body. Indeed, according to observations, ions of the water group accounted for 70–80%. Furthermore, at a distance of about 160 thousand km, a theoretically unpredicted 'cometopause' was discovered, separating regions with different concentrations of comet ions.

VEGA was the first probe to fly near Halley's comet (March 6, 1986) among a flotilla of other vehicles directed to the comet, including the GIOTTO vehicle of the European Space Agency.

During the meeting of VEGA 1 and VEGA 2 with the comet, the PATHFINDER (Pilot) experiment was carried out for the first time in the world: the VEGAs promptly transmitted information to Earth, which made it possible to significantly refine the position of the comet's nucleus, from 1500 to 40 km. Thanks to this, the European apparatus GIOTTO was able to approach the nucleus at a distance of 600 km; The measurements performed by GIOTTO fully confirmed the main characteristics of the comet's nucleus according to the data of the VEGA spacecraft.

The planetary part of the VEGA program also provided unique information — balloon measurements of meteorological parameters carried out in the Venusian atmosphere at altitudes of 53–55 km. These measurements have made a great contribution to the understanding of atmospheric processes on Venus.

RZ was one of the initiators of the development of work on X-ray astronomy in the USSR. Thanks to him, international cooperation in the field of X-ray astronomy arose at IKI: four orbital observatories with results now known to the whole world.

Also in the 1980s, RZ returned to problems with the relationship between chaos and regular structures in turbulence, which had interested him since the time of the Novosibirsk period. A series of publications appeared (co-authored with G M Zaslavsky and others), in which the concept of a 'stochastic web' and regular structures was developed. The title of one of the articles is characteristic: "Chaos — how regular can it be?" This series of studies contains a significant development of our understanding of chaos.

During Perestroika, RZ was a member of Gorbachev's circle of advisers and was elected to the Supreme Soviet of the USSR. However, RZ's unwillingness to strictly follow the instructions of the party organs led to the termination of these relations.

Since 1990, R Z Sagdeev has been a professor at the University of Maryland in College Park (USA). During these years, he has studied the interaction of collisionless shock waves with cosmic rays (together with M A Malkov and others). They developed models explaining, in particular, the well-known 'knee' effect in the spectrum of cosmic rays.

Since 2015, RZ has been a professor emeritus at the University of Maryland. He leads an international Zoom seminar covering a wide range of topics, from physics to epidemiology, from literature to the history of science.

In 1986, Academician R Z Sagdeev was awarded the title of Hero of Socialist Labor of the USSR. RZ has received many other Soviet and Russian awards and prizes, as well as prizes from international scientific bodies. He is a member of the Academies of Sciences of the USA, Sweden, and Hungary, the Max Planck Society (Germany), and the Pontifical Academy of Sciences.

RZ is a versatile person with a wide range of interests. He has an excellent knowledge of fiction and historical literature, understands and enjoys painting, and is interested in the history of religions and their role in modern society. RZ has always taken an active stance on critical policy issues in science, society, and nuclear weapons control. He knows how to boldly express his opinion and justify it.

On behalf of his students, colleagues, and friends, we wish Roald Zinnurovich a wonderful birthday and wish him good health and creative activity.

A G Aganbegyan, A I Vainshtein, G I Dudnikova,
V E Zakharov, L M Zelenyi, E A Kuznetsov,
A G Litvak, R I Nigmatulin, D D Ryutov,
A N Skrinsky, R A Sunyaev, M P Fedoruk