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YAKOV BORISOVICH ZEL'DOVICH

(On the Occasion of his Fiftieth Birthday)

Ya. A. SMORODINSKIĬ and D. A. FRANK-KAMENETSKIĬ

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ACADEMICIAN Yakov Borisovich Zel'dovich celebrated his fiftieth birthday on March 8, 1964. He still continues with youthful passion to display his creative energy in all new domains of theoretical and experimental physics. Zel'dovich has notably succeeded in not allowing his scientific enthusiasm to diminish and to this day he is still finding more profound approaches to the numerous problems with which has has been concerned during his scientific life. His first field of activity, which is still far from being exhausted, was chemical physics. Leaving the nine-year school (the only educational institution which he officially attended) he became a laboratory assistant in the Mekhanobr Institute (for mechanical processing and dressing of useful minerals).

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During an excursion to the Leningrad Physicotechnical Institute, the seventeen year old Zel'dovich made such an impression with his questions on the director of the laboratory (S. Z. Roginskiĭ, former corresponding member of the U.S.S.R. Academy of Sciences) that the latter, with the help of A. F. Ioffe, arranged a transfer for the talented youth to the Leningrad Physico-technical Institute. The Institute was soon split up and he became a laboratory assistant in the Institute of Chemical Physics, where he took part in experiments in S. Z. Roginskiĭ's laboratories. The first published work to which Zel'dovich contributed, with S. Z. Roginskiĭ and L. A. Sena as joint authors, dealt with the mysterious phenomenon of "remembrance" of crystalline shape in the repeated crystallization of nitroglycerine. Of course, neither this work, nor the difficult measurements (carried out with S. Yu. Elovich) of the kinetics of the catalytic oxidation of CO by MnO_2, marked out the scientist's future path, but it is important to note that his theoretical work was preceded by a serious mastery of experiment. It is not without reason that, among the numerous pupils of Yakov Borisovich, a number of first class experimentalists are to be found alongside the theoreticians. From a study of the processes of heterogeneous catalysis, the scientific interests of the young investigator naturally moved on to their theoretical basis—the absorption theory for a heterogeneous surface; at the age of twenty he produced his first independent work, devoted to the theoretical interpretation of Freundlich adsorption isotherms. Here the power of the theoretician can already be felt. It was a case of a difficult mathematical problem, the general methods of solution of which had been a subject for dispute among specialists: the solution of a first-order integral equation, i.e., finding a spectrum from the integral effect. By a simple method of approximation, Zel'dovich produced a complete solution for the case which interested him. This work, together with the work of M. I. Temkin, who was going in a rather different direction, served as the beginning of the whole new field of chemical physics—the theory of adsorption and catalysis on heterogeneous surfaces, to which extensive monographs are now dedicated. Later the author himself moved away from these questions—perhaps the only case in his scientific career. The next stage was his participation in wide-ranging work under the inspiration and general guidance of N. N. Semenov on the combustion oxidation of nitrogen. Here there appeared another trait of the scientist—an inclination towards problems which have important practical aspects, and a strong interest in the practical applications of results which had been obtained. The work in question concerns an extremely important and now practical task: the fixation of atmospheric nitrogen. It was not published as an individual monograph until several years later (jointly with P. Ya. Sadovnikov and D. A. Frank-Kamenetskiĭ). Zel'dovich soon became the director of a complex of experimental theoretical and technical operations. The production engineer, G. A. Barskiĭ, who became one of his closest pupils and long standing collaborators, was invited to handle the technical and economic side. Zel'dovich has been working on this problem right up to the present time: articles by him and his colleagues appear in his collection "The Fixation of Atmospheric Nitrogen" which has just appeared.

Zel'dovich is one of the founders of an important branch of chemical physics—macroscopic kinetics, which investigates the laws of a chemical reaction in connection with the physical phenomena of diffusion and heat transfer, phenomena which complicate the real course of a reaction both in nature as well as in technology. To him must be given credit for the basic result in the diffusion kinetics of porous media: the velocity of the total reaction on a porous surface is the geometric mean of the reaction velocity and the diffusion velocity. Continuing the classic investigations of N. N. Semenov and his school, Zel'dovich made a particularly noteworthy contribution to that important branch of macroscopic kinetics which is concerned with combustion theory. Together with D. A. Frank-Kamenetskiĭ, the first of his many pupils (and he had pupils from the time when he was twenty onwards) he found a quantitative link between the propagation velocity of a flame and the kinetics of the chemical reactions within it. They were the first to understand that the problem of the stationary flame distribution mode is a problem with its own significance. Zel'dovich later investigated this problem in an exhaustive manner and accurately established the essential approximations and idealizations, in particular the importance of the assumption about the zero reaction velocity in the neighborhood of the initial state. Further investigations into this question produced nothing that was significantly new. He continues the development in depth of flame-propagation theory to this day. As early as 1962, his graduate students A. G. Istratov and V. B. Librovich established with accuracy the method of approximation which they had used in calculating the flame velocity for individual chain reactions and obtained remarkable agreement with the measurements which another of his pupils, A. I. Rozlovskiĭ had obtained using chlorine-hydrogen compounds. Zel'dovich is responsible for the refined mathematical solutions of such basic problems of combustion theory as ignition by an incandescent surface, the limits of flame propagation and many others. The very setting of the ignition problem presented considerable mathematical difficulties which he overcame brilliantly by finding the invariance of the equations in relation to a certain transformation group. It must in general be said that some special sense invariably suggests to him the mathematical approach needed for the particular problem, which frequently produces what are innovations even for mathematicians. Through him there arose a large scientific school that concerned itself with theoretical and experimental investigations of combustion reactions and worked out an original and fruitful approach to them.

In recent years the prominent mechanical engineer G. I. Barenblatt was attracted to the work, and in cooperation with him, Zel'dovich successfully applied contemporary methods of computer mathematics to combustion problems. Developing the method proposed by the English research worker, Spalding, they calculated the flame propagation velocity for a number of complicated systems by actually analyzing the result of the solution for the stationary mode, and brilliantly confirmed in this way the conclusions of the approximate theory.

Work on flame stability belongs to this chapter of events. The stability of the uniform propagation mode was successfully proved, based only on the monotonic behavior of the temperature distribution curve. Zel'dovich and his school are responsible for the very idea of studying high temperature chemical kinetics by measuring the flame speed, as well as for its successful experimental realization.

During the Second World War, combustion theory acquired a practical significance of vital importance. The well-known work "On the Combustion Theory of Gunpowder and Explosive Substances" shows the nature and extent of his work in that period and the monograph "Reaction Momentum of Solid-Fuel Rockets" (in collaboration with M. A. Rivin and D. A. Frank-Kamanetskiĭ) is a comprehensive work on combustion mode stability in a semi-enclosed space.

With these works, Zel'dovich established the physical basis for the internal ballistics of solid-fuel rocket motors. The importance of this science in our times cannot be over-estimated. Starting from the fact that the combusion of gunpowder takes place in the gaseous stage (similarly to the manner in which, according to A. F. Belyaev, the combustion of evaporating liquid explosives takes place) after the stage of relatively low temperature decomposition—the gasification of the powder—he obtained expressions for the powder combustion velocity and its dependence on temperature and pressure.

Fundamental innovations were the analysis of non-stationary modes, the understanding of non-stationary combustion velocity which Zel'dovich introduced and the clarification of the limits of stability of the stationary modes.

The transient mode theory made it possible to explain the extinguishing of the powder when pressure is decreased and the increased combustion velocity at increased pressure. From this theory can be derived the amplification of sound when reflected from a burning surface, which leads to undesirable oscillations in solid-fuel rocket motors. The same theory explained a malfunction in these motors consisting of a flame-out followed by extinguishing of the powder.

Zel'dovich recently published, in cooperation with P. M. Zaĭdel', a new main work on combustion, in which combustion is considered not in the flame propagation mode, but in the induction mode, where a compound is heated up by local reaction heating and by heat transfer from the flame. In the first years after the war, Zel'dovich opened a Combustion Process department in the Moscow Mechanical Institute and delivered a course of lectures on the subject. Notes made on two parts of this course, revised by him with V. V. Voevodskiĭ and D. A. Frank-Kamenetskiĭ and then lithographed, still enjoy great popularity among students, although they are out of print.

The combustion theory was for him a stepping stone to a series of new directions in science.

Thus, the transition from the study of chain reactions of combustion to nuclear chain reactions was quite natural. And indeed, shortly after the appearance of a nuclear physics section in "Uspekhi Fizicheskikh Nauk" Zel'dovich and Yu. B. Khariton published a survey entitled "Fission and Chain Disintegration of Uranium"—the first comprehensive exposition in the world's scientific literature of this series of problems, an exposition which contained a great many original and fundamental results, and which is valued to this day as a classic work on the scientific basis of nuclear energy theory.

Another important field into which he moved, starting from combustion theory, was the theory of shock waves and detonations.

Detonation combustion was investigated long ago; in the gaseous state the reaction propagates with a velocity of the order of 2 km/sec and in the condensed state with a velocity of the order of 7—8 km/sec.

At the beginning of the 20th century Chapman and, working independently, Jouguet explained detonation combustion by deducing that the reaction was produced by a shock wave running through the material; the energy of the shock wave in its turn was replenished from the heat of the reaction. But in order to explain the fixed value of detonation velocity under given conditions they introduced a supplementary hypothesis, namely that the velocity of the wave relative to that of the detonation products was equal to the local velocity of sound. In the course of forty years, this hypothesis did not obtain any firm foundation. Meanwhile research workers, unfamiliar with gas dynamics, who were investigating detonations, for long rejected groundlessly the shock mechanism of detonation theory and devised their own highly fantastic hypotheses.

Zel'dovich managed to bring order into this question when he succeeded in a very simple manner in giving a foundation to the Chapman-Jouget hypothesis, starting from general considerations on the uninterrupted nature both of the progress of the reaction and of its energy balance in the material immediately behind the shock wave. Independently, but later, J. von Neumann, one of the most outstanding mathematicians of our century, arrived at the same foundation for the hypothesis.

These theoretical investigations were strengthened by experiment. Together with B.V. Aĭvazov, he produced a detonation with increased propagation velocity by passing a wave from a wide pipe into a narrow one; the wave in the wide pipe pressed against the wave in the narrow one. To prove that the velocity was increased, they caused the wave in the narrow pipe to collide with detonation wave coming towards it (this latter wave was not pressed from behind) and observed the deflection of the collision front.

Zel'dovich made many new theoretical and experimental investigations of detonations. He first explained the phenomenon of detonation limits, which consists in the fact that even with a small decrease in detonation velocity the wave ceases to propagate as a result of thermal or mechanical losses. He explained this very simply: a relatively small drop in temperature in the detonation front leads to a highly significant slowing down of the reaction and this in its turn increases decisively the zone where losses take place.

The theory described applies to plane waves. In fact, the front of a traveling wave is distorted near the limit—a spreading spiral break is formed in it. Increasing the resultant velocity leads to an increase in the ignition velocity of the compound. The basic theories of this phenomenon, the so-called spin detonation, were also developed by Zel'dovich.*

It is not possible here to mention all of Zel'dovich's works on detonation. We will only say that after his efforts, detonation theory became an integral part of gas dynamics.

Apart from detonation waves, he studied extensively ordinary shock waves in inert chemical compounds. Particularly interesting is his simple theory on the propagation of converging spherical shock waves. For a rigorous solution this problem demands complex numerical calculations; starting from simple physical premises, Zel'dovich produced an analytical procedure of perfectly satisfactory accuracy.

Another interesting problem, first solved by Zel'dovich, is that of the high velocity impact on the surface of a medium. This is one of the first of the special self-similar problems. It is interesting, that in the case of such an impact, the shock-wave momentum

*In a later erratum [UFN 83, 196 (1964)] Ya. B. Zel'dovich states that the most important qualitative concepts in this question are due not to him but to K. I. Shchelkin.

received by the medium can be much greater than the momentum of the striking body because of the momentum of the scattered matter which is borne in the opposite direction.

The participation of conduction processes in shock-wave propagation was considered long ago. It happened, under known conditions, that a strong transfer of thermal (radiant) energy can smooth out a shock. Zel'dovich showed that this is correct only in that approximation where the radiant energy range is considered to be insignificantly small; at a finite value of the range the pressure discontinuity is always conserved. Attention must also be drawn to Ya. B. Zel'dovich's work on the radiant energy transfer not connected with the shock wave. This is dealt with principally in his work on the cooling of air by radiation (in cooperation with A. S. Kompaneets and Yu. P. Raĭzer) where for the first time account was taken of the sharp variation in the transparency of air at 10,000°, due to ionization. It leads to appearance of the characteristic thermal wave whose existence Zel'dovich deduced theoretically.

Another example of non-linear conduction is the problem of heat propagation from a point source. In distinction to linear conduction, a steep traveling front arises here.

Later, together with G. I. Barenblatt, Zel'dovich analyzed also the thermal dipole. This problem is the thermal analogy of the short blow problem.

A great part of his creative work, particularly in later years, is devoted to the theory of elementary particles. Here is clearly displayed his remarkable intuition and ability to see the new qualitative peculiarities of a problem where no clear theory had been formed before.

A more convincing example is doubtless his discovery in 1955 (in cooperation with his young and talented pupil S. S. Gershteĭn) of the phenomenon of the conservation of a vector current in weak interactions. The close analogy with electrodynamic interaction, which was discovered by him, lies now at the base of the theory.

The universality of the theory of weak interactions permitted Zel'dovich to forecast the life time of π-meson β decay. Experiments performed in Dubna and Geneva revealed this rare process and confirmed what theory had forecast.

Zel'dovich and Gershteĭn's work on the theory of the catalysis of nuclear reactions by negative muons led to the development of a new trend—μ-mesic chemistry (the interaction of muons with the electron shells of atoms) and inspired some excellent experiments which were carried out in Dubna.

Involvement with nuclear theory and the theory of elementary particles led Zel'dovich to a new field—astrophysics. The beginning of this quite recent period was marked by a series of outstanding lectures and many articles on the application of the ideas of the general theory of relativity to questions of the evolution of the stars and the universe. Brilliant suggestions he had made about the role of the neutrino in the development of the universe indicated new paths along which further investigations might be carried out. And in this new field, his work was characterized by the way it unexpectedly cut across ideas and methods of extreme variety.

The many sided nature of Zel'dovich's activity can be seen in one more example. It is well known that a student learning higher mathematics frequently meets great difficulty in attempting to apply his knowledge to the analysis of physical and mechanical processes. Zel'dovich devised a new teaching approach in which the necessity of differentiation and integration was evident from the problem that was set.

Using this approach, he wrote his "Higher Mathematics for Beginners" in which the exposition is arranged so that all the mathematical concepts are closely limited to concrete physical phenomena. The book was well received by teachers in establishments of higher education. They considered it as a new spirit in the task of spreading mathematical knowledge. It ran through two huge editions in this country and was also published in a number of other countries.

What has been said here is far from a complete catalogue of the most important fields in which Zel'dovich did brilliant work, but it may give some idea of his scientific make-up. The creative activity of a scientist increases exponentially. The circle of his activities widens as the acquisition of new interests enhances the earlier ones. In our century of narrow specialization Zel'dovich can be seen to approach more closely the ideal of the universal scientist, so rare in our days. His talent as a theoretician and experimentalist, his passionate love of science and his indomitable temperament stand out brilliantly. An analysis of the dynamics of his scientific creative work gives firm grounds for believing that it is entering a period of highest creative accomplishments. And so we wish Yakov Borisovich Zel'dovich these successes, for the good of science and humanity.

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