THE DYNAMIC HIGH PRESSURE WORK OF ACADEMICIAN YA. B. ZEL'DOVICH (1914-87)

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Academician of the Soviet Union Yakov Borisovich Zel'dovich was born in Minsk, USSR, on March 8, 1914. He passed away at age 73 in 1987. When he was a child, his family moved to Leningrad where he attended various secondary schools. Upon his graduation at the age of fifteen, he became a laboratory technician in the Mekhanobor Institute, assisting in various projects involved with the dressing and processing of industrially useful minerals. Two years later, at a field trip to the Leningrad Physicotechnical Institute, young Zel'dovich had the opportunity to present a number of his scientific ideas during a discussion session arranged for the group by the Institute Director, S. Z. Roginskii.

Impressed with the obvious ability of the young man, Roginskii arranged, with Academician A. I. Ioffe, for his immediate transfer to the Institute.

In the early years, the young Zel'dovich limited his work to various problems in surface phenomena such as adsorption, kinetics, and catalysis. He completed his Candidates Dissertation in 1936, at the age of 21. His work in this field led him to his first problems in high pressure physics and chemistry. Consideration of the kinetics of reactions, combustion and the effects of pressure on reactions, led Zel'dovich very naturally into studies of detonation phenomena. In 1939, he completed his doctorate, with the thesis topic "Formation of Nitrogen Oxide in Explosions." It is interesting to note that all his graduate studies were carried out without the benefit of any university course work whatsoever.

During his research on vapor liquid equilibria, Zel'dovich became interested in vapor-liquid critical phenomena, particularly in metals. He realized that in the critical region, there was the possibility that for metals, the classical van der Waals behavior did not coincide with what is now called the Mott transition. In 1943, he coauthored with Landau[1] the proposition that there could perhaps be two critical points, both connected to a triple point where liquid metal, conducting metal vapor and dielectric metal vapor were all in equilibrium. Although Zel'dovich did not pursue this particular area further, this paper was a forerunner of the brilliant work of Franck[2], and Hensel[3] which gave the first experimental clues as to the existence of such phenomena in the critical region of metals. This field is extremely active to this day, with Hensel continuing his work on the alkali metals, and the groups of Shaner[4] in the U. S. and Alexeyev[5] in the USSR pursuing the more refractory metals to still higher critical pressures and temperatures. Interesting new theoretical results have also been obtained by Ashcroft[6].

As mentioned previously, his early work in combustion led Zel'dovich to consideration of the Chapman-Jouguet hypothesis for detonation. These two earlier investigators argued that detonations were driven by shock waves, and the energy required to sustain the shock wave was provided by the energy released in the detonation. Their assumption of a constant detonation velocity also required, from a purely hydrodynamic standpoint, that the mass velocity of the detonation products plus the sound velocity in the detonation products was equal to the detonation velocity.[7,8] This latter assumption could not be justified by any known physical model, and as a result, the role of the shock wave in the detonation process was not accepted for many years. In 1940 Zel'dovich first introduced the concept of the steady state reaction zone behind the detonation front, and the corresponding energy balance around this zone.[9] This model gave rise to what is now called the Zel'dovich, von Neumann and Doering (ZND) model,

The twenty-five year old scientist developed and published his ideas at least two years before his colleagues in the West.[10,11] He then followed with other papers refining and experimentally verifying the model.[12,13] This model has served as the starting point for all detonation-hydrodynamic calculations for the past forty-five years, and is still a topic of intense interest today.[14,15]

Having clarified the issue of steady state, one dimensional detonations, Zel'dovich turned his attention to the unsteady state, multidimensional detonation problem. With his collaborator K.I. Shchelkin, he developed the theory of "spinning detonation" in which a part of the detonation front moves circularly and at an oblique angle to the direction of the detonation[16,17]. This phenomenon has been studied extensively in the U.S. in both gas[18,19,20] and liquid[21,22] high explosives by Duff and co-workers, and provides a natural point of departure from the simple theory of detonation.

His work in detonation naturally led Zel'dovich into the area of high pressure and shock waves. In his earliest work in high pressure physics, he pointed out that the measurements usually made in shock wave experiments provide only pressure, volume and energy.[23] For the first time, he pointed out that this shortcoming could be corrected by making Hugoniot measurements starting with the same material but at different densities, using dispersed or porous media. He also, in the same paper, pointed out both the utility and shortcomings of temperature measurements taken in shock wave experiments. Soviet investigators followed the publication of this paper with extensive programs in shock wave temperature measurements[24] and Hugoniot experiments on porous metals.[25] This work will be cited later.

In the course of studying critical phenomena[26], Zel'dovich was the first to note that anomalies on fluid isentropes could lead to shock fronts occurring during the high pressure release process. This discovery made possible the explanation of the extremely smooth spallation planes encountered in recovery experiments on iron and its alloys shocked through the 130 kbar phase transition.[27] In 1980 this effect was finally observed, as Zel'dovich had predicted much earlier, near the liquid-vapor critical point[28] Shortly thereafter, the effect was proposed by Zel'dovich as a tool for carrying out studies of the approach to equilibrium near the critical[29].

As his involvement in high pressure shock wave phenomena increased, Zel'dovich became interested in the thermal effects which are encountered in very high pressure shock waves. In some of his earliest work in the field he showed that radiative shock fronts in air must be discontinuous, in contrast to shock fronts where viscosity is the dissipative mechanism.[30] Subsequently, with his student, the late S.B. Kormer, he carried out the first measurements of temperature in a shock compressed solid[31].

Zel'dovich also realized very early in his career the power of theory in anticipating phenomena which were later observed experimentally at high pressures. In 1944, he and Landau, amplifying on ideas developed in their 1943 paper, predicted band gap closure with an increase in pressure.[32] This has been a topic of continuing interest, with the advent of increased capability in both static[33,34] and dynamic[35,36] experimental techniques. He collaborated with Gandelman in predicting the transition of nickel metal to an insulator at extremely high pressures[37], an effect most recently confirmed by McMahan[38], using the most sophisticated computational band gap theoretical techniques. And finally, he derived the relativistic limits for equations of state at very high density.[39] He has followed this high pressure interest to the present, in his current investigations of the properties of neutron stars[40] and other newly discovered astrophysical objects.

Most recently, Zel'dovich has returned to solve a very important practical problem involving detonation. Referring to his original work[41,] he showed[42] that damage from deflagrations can be comparable to damage from detonations, because of the increased duration of the pressure pulse in the deflagration case. He also showed that in the case of rough confining boundaries, such as might be found in rough pipes or mine shafts, for example, the losses in the deflagration (or detonation) process caused by this roughness do not tend to damp the combustion process. This has great importance in safety engineering, in protecting against the structural damage caused by these processes.

It is not possible to discuss the achievements of Zel'dovich in the field of dynamic high pressure without also describing the work of his students, S. B. Kormer and V. E. Fortov and his colleague, L. V. Al'tshuler. The strong influence of Zel'dovich on these men, and their subsequent accomplishments were responsible for establishing the clear leadership of the Soviet Union in the field of dynamic high pressure. So dominant were Al'tshuler and Kormer in this field that all the significant dynamic high pressure experiments were done initially by this group. Extremely high pressure measurements,[43] temperature measurements,[31] optical measurements,[44] electrical conductivity,[45,46] and its mechanism,[47] melting[4,8] kinetics of electronic and thermodynamic processes,[49,50] transport properties,[51] and sound velocity[52] were all done in the Soviet Union long before scientists in the West were able to carry out similar measurements.

In recent years, leadership in the dynamic high pressure field has been assumed by a younger student and colleague of Zel'dovich, V.E. Fortov. Fortov has created an entirely new field in the area of dynamic high pressure physics. Starting from his original work in dense plasmas as a student, Fortov has applied dynamic techniques to the measurement of dense plasma properties. Formerly, theories of dense plasmas were formulated with little, if any, hope of verification. Now, Fortov and his group are systematically opening up the high temperature, extended volume regime with both equilibrium and transport property measurements on both metals and nonmetallic substances.[5,53,54,55,56,57] This work has already stimulated intense interest in the Soviet Union[58,59] and the West[60,61], and is providing new stimulus for theoreticians working on the description of dense plasmas. In the area of applied research, Fortov was responsible for design of the meteorite impact shields for the very successful "Vega" space probe of Halley's comet[62].

The work of Al'tshuler, Kormer and Fortov is characterized by an unusually innovative approach to dynamic experimentation, the courage to address very difficult experimental problems, the choice of the most significant problems to address, an exceptionally thorough grasp of the critical experimental variables and their significance, and finally, an unusually deep intuition for the fundamental physics they addressed in their high pressure experiments. Certainly, these three outstanding Soviet scientists are also due recognition for the many achievements of their distinguished careers.

Textbooks written by Zel'dovich and his co-workers have served a generation of physicists throughout the world. Two such texts in the high pressure field are "Physics of Shock Waves and High Temperature Hydrodynamic Phenomena", with Yu. Raizer, and "Theory of

Detonation", with A.S. Kompaneets. These two texts alone have been extensively reprinted in many countries, and are still in continued use today.

Finally, note must be taken of the tremendous volume of original and insightful work done by Zel'dovich in other fields. It is a tribute to his creativity and brilliance that even though his work in shock waves and detonations only occupied a part of his scientific career, he still remains the single dominating historical figure in the dynamic high pressure field. It should also be recalled here that much of his most significant work as a young man was carried out at a time when his country was fighting desperately for its very existence. There were no scientific meetings, no visits abroad, only the occasional collaboration with local colleagues. The first priority for all his efforts was related to defense matters.

In looking back at the long and productive career of Academician Zel'dovich, one cannot fail to note that having established a particular field, or area within a discipline, he often returns to touch on significant issues, frequently with former colleagues. He is generous in his recognition of those experimentalists and theoreticians who have worked with him.[63] Certainly, having once been a colleague of Zel'dovich is to have gained a colleague for life.

Just as Professor P.W. Bridgman opened many exciting avenues for research in the static high pressure field, so Academician Zel'dovich has done the same for the worldwide community of dynamic high pressure scientists and engineers. He is a worthy representative of his country, the community of high pressure scientists and indeed, of the scientists of the entire world.

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