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Academician Zeldovich and the foundations of disc accretion

N I Shakura

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Abstract. The author draws on his memories to review the decisive contributions of Ya B Zeldovich to the formation and development of the theory of disc accretion onto black holes and neutron stars in binaries. A theory developed by N I Shakura and R A Sunyaev in the early 1970s under the guidance of Ya B Zeldovich predicted these objects to be the brightest X-ray sources in the sky and defined the prospects for research in X-ray astronomy and high-energy astrophysics for decades ahead.

Back in the summer of 1963, a book titled *Higher Mathematics for Beginners* caught my eye in a bookshop in Bobruisk, Belarus, where I, then a youngster just graduated from a secondary school in the urban settlement of Parichi in the Gomel region, happened to be on some business. Although the author, Ya B Zeldovich, was a name I had never heard of before, its contents has drawn my attention to the book for the following reason.

In those long-past times, the school math curriculum stopped at taking limits. Preceding them were elementary functions, one of which was (and surely still is) a parabola. For this function, it was typically required to find the positions of either the minimum (up-open case) or the maximum (down-open case). And here I remember our math teacher Alfred Viktorovich Baranovskii, who also taught us physics and astronomy and who was a teacher by calling (alas, he left this world in 2004). When explaining the parabola problem with then-current methodologies, he used to say: "In higher mathematics, all this can be done in an easier and more beautiful way." Of course, as anyone even slightly familiar with higher mathematics knows, the way this is done consists in taking the derivative of the function and then equating it to zero, which, for a parabola, results in a linear equation in x. This is, of course, very simple, but at the time, to repeat, the school math program stopped at taking limits and did not cover derivatives. Now much older than Alfred Viktorovich was when he taught school mathematics to our generation, I believe that whatever you do, be it small or big — and teaching is, of course, big — time-tested methods are always best.

Now, some will say that all things develop and many become out of date before you can say Jack Robinson. But it is the mission of a teacher to be able to feel whether or not all his students are ready yet to accept new ideas. Although Alfred Viktorovich did not conduct special sessions for advanced pupils, he allowed us admission to the school's physics classroom. And what a fascinating and diverse place it was!

On the self-educational level, the source of my mathematical knowledge was the publications that I ordered and received by mail from Moscow State University (MSU), the country's leading university. Interestingly, A V Baranovskii, our school teacher, and Yakov Borisovich Zeldovich, Academician and MSU Professor, had a common feature in their teaching style: they knew much more than they told to an audience. Information should be dosed out, and the doses should be reasonable. If a pupil failed to do homework, Alfred Viktorovich, his eyebrows sternly knitted used to threaten him with an F in the grade book — a threat which, while feared most, was rarely carried out.

Yakov Borisovich usually concluded his lectures with the question: "Are there any questions?", and usually there were none. "Then", he used to say, mimicking (he confessed) his school teacher's phrase, "it is me who will ask you questions." This intention, however, often remained just that.

Ya B's students, postgraduate and undergraduate alike, spent most of their time in those days in his department at the Institute of Applied Mathematics (IAM), then directed by, and now named after, Mstislav Vsevolodovich Keldysh. Ya B quite often used to make a bet for a bottle of mineral water with young people, and I remember the department's rooms having their window ledges loaded with such bottles, with written notes on the labels as to who lost, who won, and what the bet was about. These bets brought Yakov Borisovich somewhat closer to his young students, making them less afraid to say something wrong. Admittedly, though, there was an invisible red line in how to be behave with respect to him: crossing this line could turn attraction to repulsion, so to speak.

But back now to my visit to Bobruisk in 1963. Having bought the book, I started browsing it sitting in a small cosy garden on Bakharev street. Its first pages were the usual school stuff like path, velocity, acceleration, etc. A nice young Gypsy girl distracted me from reading the chapters on higher mathematics and in due course was paid for her fortune telling services before we departed. The payment, incidentally, was two fifteen-kopek coins, something young readers may not have heard of. To give an idea, the per kilometer cost of a bus trip between Bobruisk and Moscow — and I made such trips and back many times because there was no direct railway between the two cities — was then about two kopeks.

With the task ahead of going to Moscow and taking admission exams for the astronomy subdepartment of the MSU Faculty of Physics, the newly bought book was no longer given any attention. The decision in favor of astronomy came when I was already in the admission board room,

N I Shakura Sternberg State Astronomical Institute,
Lomonosov Moscow State University,
Universitetskii prosp. 13, 119991 Moscow, Russian Federation
E-mail: nikolai.shakura@gmail.com

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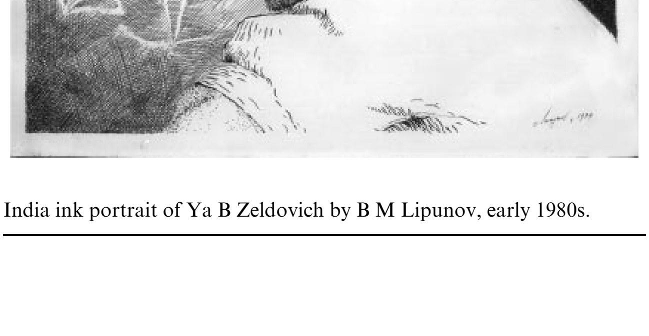
one determining factor being, quite naturally, Gagarin's flight only some two years earlier. But what really inspired my choice was a book, yet another book that somehow found its way to the middle of nowhere in Belarus: *Essays About The Universe* written by B A Vorontsov-Velyaminov, a professor of astronomy at Moscow University. When already an MSU undergraduate, I attended his lectures and was, of course, examined by him — something I would never have imagined when studying his classic manual *Astronomy* in a secondary school two or three years before.

In my first three years at MSU, Ya B Zeldovich was nowhere in my periphery, nor did I ever remember the book I had bought in Bobruisk. The book was absent from our list of recommended texts — by no means because it was bad, but because the academician intended it as a self-education book on mathematics for beginning engineers and technicians. Interestingly, a photo exists showing Ya B Zeldovich presenting his book *Higher Mathematics for Beginners* to Pope John Paul II. Academician Ya B Zeldovich is known for more than ten high-quality books on a wide range of topics in the sciences.

My first meeting with Yakov Borisovich was like this. When I was in my third year, a meeting was arranged by the Dean of the Faculty of Physics between the faculty students and the editorial board of the *Physics–Uspekhi* (*UFN*) journal, the Large Physics Auditorium being the venue. I was, of course, very impressed with the brilliance of Eduard Vladimirovich Shpolskii, the Editor-in-Chief. Yakov Borisovich Zeldovich was silent the whole time, sitting with his densely hairy hands crossed under his chin, and there seemed to be something unconventional about him. Later on, already as his co-worker, I learned that he had never been a full-time undergraduate student at any higher education institution. Having graduated from a ten-year school in what was then Leningrad in 1930, he went to work as a laboratory technician at the Institute of Mechanical Processing of Minerals for some time and then at the Institute of Chemical Physics (ICP) where, at the age of twenty (!), he began his postgraduate research under Nikolay Nikolaevich Semenov and where it took him a fantastically short time to get to the very top of the academic career ladder.

A year later, in the fall of 1966, we, the fourth-year astronomy undergraduates of the Faculty of Physics, found ourselves enrolled in a new dedicated lecture course, 'The structure and evolution of stars', to be taught by Ya B Zeldovich. It was at these lectures that my first personal contact with the academician occurred. The lectures were held on Fridays, and on Thursdays Ya B led a joint astrophysics seminar (JAS) at the P K Sternberg State Astronomical Institute (MSU SSAI), both for full-fledged scientists and for young higher education graduates. Undergraduates did not have this seminar in their curriculum and could only drop in on when possible. When Ya B finished his first lecture, he asked if there were in the audience those wishing to receive topics for their course theses and could they please stay on for a while. I was among those few who did. When my turn came, he asked me whether I had been at the JAS session the previous day and whether I had heard the talk on the (then mysterious) sources of cosmic X-ray radiation, and when I twice said yes, he made a suggestion. The suggestion was to calculate the structure and spectrum of the radiation of a strong shock wave that arises near the surface of a neutron star due to gas falling onto the star.



India ink portrait of Ya B Zeldovich by B M Lipunov, early 1980s.

It was the fall of 1966, and within the next few years a number of breakthrough discoveries would be made in astronomy. In 1967, a team led by the British astronomer Antony Hewish would discover radio pulsar as a new class of neutron stars. Observations made aboard cosmic observatory Uhuru, the first dedicated orbiting X-ray observatory, would shed light on the nature of sources of cosmic X-ray radiation.

A few weeks after the academic year began, Valentina Yakovlevna Alduseva, the academic secretary of the Astrophysics Department and an SSAI researcher, approached me to finalize my theme of the course thesis. "Kolya," she said, "it will be the *accretion* of gas onto a neutron star, Academician Zeldovich had said." I was extremely astonished because I had never before heard this mysterious word, nor had the Academician ever used it in our shock wave discussions, nor, indeed, did the standard astronomy texts of the time mention anything of the kind. Incidentally, Valentina Yakovlevna Alduseva was also the supervisor of our (that is, astronomy majors!) summer practicals in the same year, which were done at the SSAI Tian Shan Observatory near Alma Ata and which parenthetically — as is often the case — were instrumental in bringing students and staff closer together. Aware of my embarrassment about accretion, Valentina Yakovlevna was kind enough to allow me access to the research library of the SSAI (most of my fellow undergraduates had to be content with the library of learning materials). What I learned after much browsing and reading was that this word originates from the Latin word for acquiring (growth, increase), or *accrescere*. In astronomy, this term is used to refer to processes in which rarefied surrounding matter falls onto gravitating objects of various natures. In those days, more than half a century ago, the theoretical study of such astrophysical processes was in its infancy, and not surprisingly so, because no observational data were available.

Over the years since then, an immense body of information concerned with accretion processes — and indeed on a wide range of astronomical phenomena — has been accumulated and is accumulating at an ever increasing rate due to the huge range of available instrumentation and, crucially, due to the computer processing of observational data. In those far-off days of the 1960s, our computational arsenal consisted only of, besides the slide rule, Felix, a metallic hand-operated calculator, and now an item in research institute museums. (In the late 1960s, though, the MSU computer BESM started to be used by students in their laboratory work).

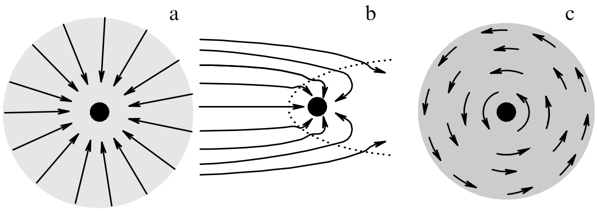


Figure 1. Types of accretion onto gravitating centers: (a) spherical, (b) conic, and (c) disk type.

On to accretion in astronomy, then. (The phenomenon is also known in geology, but this is an entirely different story.)

There are three regimes for the accretion of surrounding gas onto a gravitating object (Fig. 1). In the *spherical* regime, the gravitation center is at rest or moves at much below the speed of sound relative to the gas cloud. The *conic* regime arises when the gravitating center moves supersonically relative to the gas cloud; it produces a head-on shock in front of the center, which transforms into an oblique shock wave behind the center. In the *disk* regime, the incident matter has a significant angular moment of momentum relative to the center and is thereby prevented from directly falling onto it. In the first approximation, the gas in the disk moves along circular, near-Keplerian orbits. It is only in the presence of an effective turbulence- and/or magnetic field-assisted mechanism of moment exchange between the neighboring layers of the differentially rotating disk that disk accretion, i.e., a slow, radial, gravitational-energy-releasing motion of matter toward the gravitating center, emerges.

Ya B used to say the popular quotation from Arkady Averchenko when mentioning the history of the problem: "The history of midianites is mysterious and obscure but historians, nevertheless, divide it into three periods...." The first studies of conic accretion were carried out by Hoyle and Lyttleton [1–3] and Bondi and Hoyle [4] starting in the late 1930s and to mid-1940s. In the early 1950s, Herman Bondi [5] was the first to exactly solve the stationary problem of gas-dynamical spherical accretion onto a gravitating center. He found that a gas which is initially at rest and far away from the center accelerates as it approaches the center and, when close enough, falls onto the center supersonically at a near free fall speed. The early work on disk accretion dates back to the *Zeitschrift für Naturforschung* papers by the prominent German scientist Carl Friedrich Weizsäcker (Ref. [6], as of 1944) and his graduate student Reimar Lüst (Ref. [7], as of 1952). While the immediate subject matter of these papers, the evolution of the preplanetary gas–dust cloud, was of no direct relevance to the accretion disks currently under study, the initial equations of motion and (especially) the problem of viscous friction, of course, were and are.

In any field of science, work of outstanding value appears from time to time, with new approaches to old problems. In the field under discussion, such was the 1960 publication [8] by Fred Hoyle, where he introduced magnetic fields into the mechanism by which the rotational moment is transferred from the Sun to the protoplanetary cloud. On the other hand, looking back centuries, mention should, of course, be made of Immanuel Kant, Pierre Simon Laplace, and René Descartes, outstanding scientists who tried to explain the origins of the Solar System and put this problem on a firm scientific foundation.

The 1950s witnessed the discovery of stellar winds, which prevent interplanetary matter from falling onto the surface of ordinary stars. While stars differ in why stellar winds arise, usual singular stars (including our Sun) are not susceptible to accretion as such. A different situation arises with stars at the final evolutionary stage — white dwarfs, neutron stars, and, especially, black holes. Neutron stars are so compact that, in the case of spherical accretion, the shock wave that arises near the star surface releases tens of times the energy of a nuclear reaction. Black holes do not have any physical surfaces (they do have an event horizon!), and purely spherical accretion is not accompanied by the release of enormous amounts of energy. The only process possible is the volumetric radiation emission of the incident gas, whose temperature increases due to compression as it approaches the black hole. However, the picture of spherical accretion is significantly complicated if the incident ionized gas is magnetized. As was first shown in the late 1960s by Viktorii Favlovich Shvartsman (who sadly died very young), one of Ya B's first MSU postgraduate student recruits, pressure increases the magnetic energy so much that at a certain distance the Lorentz force can start to violate the regime of strictly spherical accretion [9]. Importantly, powerful mechanisms associated with the alternating magnetic field come into play, accelerating charge particles and hence causing them to emit nonthermal (synchrotron type) radiation. The observational signatures of such black holes are currently being poorly studied.

In the mid-1960s, two short notes — one by Ya B [10], and the other by the prominent American physicist Edwin E Salpeter [11] — drew attention to the energy release occurring in the shock wave that arises during the supersonic motion (conical accretion regime) of a black hole in an extended gas cloud. Close to the hole, the gas is heated so strongly by the passing shock wave that it starts to release radiation energy in the X-ray and gamma ranges. Even before the publication of these theoretical results, in the early 1960s, the first cosmic X-ray sources were detected by instruments on board high-altitude launched rockets [12].

In the same decade, Ya B and Oktai Guseinov [13, 14] suggested (as did Kip Thorne and Virginia Trimble [15] in the US a few years later) that black holes should be sought in pairs with ordinary stars that have not yet completed their evolution. Many of the stars in the sky are actually not single stars like our Sun but binary (or more) systems held together by the universal force of gravity. The way a binary is detected is through eclipse effects in photometric studies or through Doppler effect in spectroscopic studies. Usually, the heavier star is brighter than its lower mass companion. The gravitational field of a black hole at a large distance from it is virtually the same as for an ordinary star, i.e., the gravitational potential is close to the Newtonian one. But black holes, when treated classically (not quantum mechanically!), emit absolutely nothing according to the definition proposed by the great American scientist John Archibald Wheeler. The attention of scientists was drawn to those binary stars whose spectra give no indication of the presence of a more massive companion, and indeed small catalogues of binary systems with optically invisible companions (i.e., black hole candidates) were compiled. According to Ya B and Oktai Guseinov [13], the detection of X-ray or gamma-ray emission from such binaries would indicate the presence in them of black holes accreting matter flowing from the surface of the ordinary star. However, bright cosmic X-ray sources known by then were few, and the celestial coordinates of the black hole candidates differed from those of the first X-ray sources on the celestial sphere [15].

As noted above, my first work with Ya B consisted in calculating the structure and spectrum of the shock wave that originates near the surface of a neutron star. This work proved to be my diploma thesis and was later published [16]. At that time, my and other students' understanding of the nature of then hypothetical neutron stars and black holes greatly benefited from the fundamental reviews [17, 18] Ya B published in *Phys.-Usp.* journal jointly with Igor Novikov.

As an undergraduate, I attended lectures on general astrophysics by Dmitrii Yakovlevich Martynov, then a Director of SSAI, which paid special attention to close binary stellar systems with matter flowing from one of the stars to the other. Due to the relative orbital motion of the two stars, this flowing process results in a disk-shaped envelope forming around one of them. It seemed natural to me to consider a scenario with one of the component stars being a black hole or a neutron star.

Thus, imagine a binary stellar system consisting of a normal star and a black hole. The size of the ordinary star in this system is limited by that of the so-called Roche lobe. The normal star can increase in size as stellar evolution proceeds, and after the Roche lobe is filled, matter starts flowing from its surface to the region of gravitational attraction of the black hole (Fig. 2a). Because of the relative orbital motion of the binary components, matter does not fall directly onto the black hole but forms a differentially rotating disk-like envelope around it. Due to layer-to-layer friction, the matter that accumulates in the disk strongly heats up and starts glowing. In its rapid revolution, the matter in the disk slowly moves radially toward (or accretes upon) the black hole, loosing its angular momentum in the process. The glowing of the disk is due to the matter accretion releasing gravitational energy. Indeed, those inner parts of the disk that are closest to the hole become hot enough to emit in the X-ray range.

In a more complex accretion disk formation scenario, the optical companion does not fill its Roche lobe and flows outward in all directions via stellar wind. In this case, a head-on shock wave is naturally expected to form in the region where the stellar wind stream is under the gravitational influence of the black hole. After the passage of the shock wave, matter in the gravitational capture region of the hole starts falling onto it — but not strictly radially! Due to its rotational motion, the falling matter has a specific angular momentum, which is somewhat greater than the specific orbital angular momentum of the hole. When falling with its angular momentum conserved, the matter takes over the orbital motion of the hole and then, at a certain characteristic distance from the hole, swirls around it to form a disk (Fig. 2b). And then, well, disk type accretion again!

Replacing the black hole by a strongly magnetized neutron star in the binary system has a consequence that the stellar magnetic field starts destroying the accretion disk at a distance of about a hundred star radii. The accreting matter then starts rapidly falling along the magnetic force lines, encountering the surface of the neutron star in the vicinity of the magnetic poles. Because magnetic and geographic poles are usually far apart, the rotation of the neutron star causes it to be observed as an accretion pulsar.

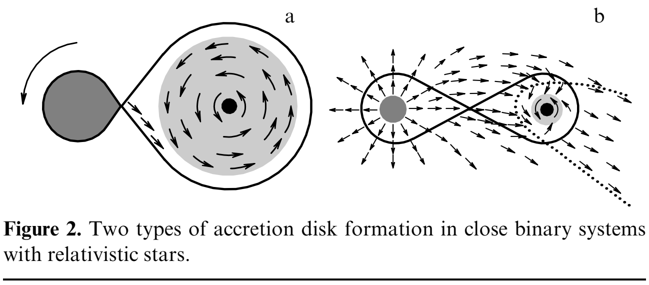


Figure 2. Two types of accretion disk formation in close binary systems with relativistic stars.

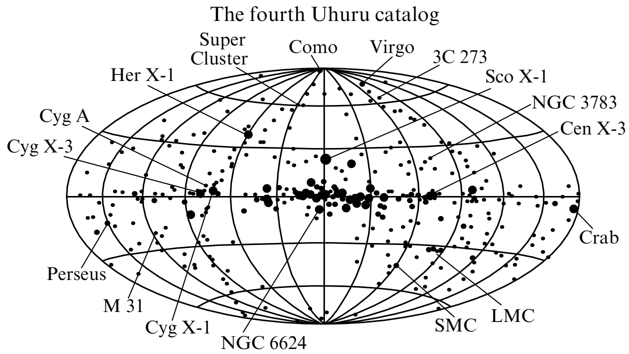
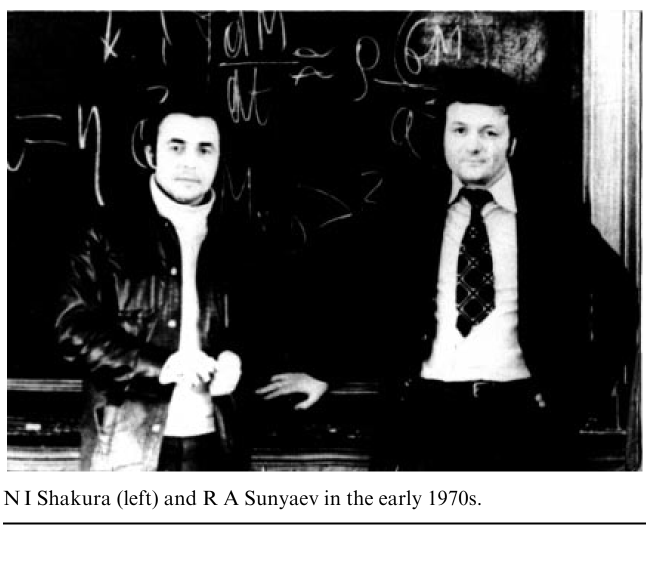


Figure 3. The first map of the X-ray sky obtained from the Uhuru satellite [19].

The presence of accreting black holes and neuron stars in binary stellar systems was first detected in the early 1970s by an experiment aboard the US purpose-built satellite Uhuru. The satellite was launched into a near circular orbit about 500 km high from the Italian marine platform San Marco off the coast of Kenya, and its name (which is Swahili for *freedom*) is due to the fact that the launch date, 12 December 1970, was Kenya's Independence Day. Recognition is not always quick to come in science, and it was only in 2002 that the mission project leader Riccardo Giacconi, a US astrophysicist of Italian origin, was awarded the Nobel Prize in Physics for this pioneering work (see Fig. 3).

Virtually simultaneously with the discovery of accreting black holes and neutrino stars in binary stellar systems, the foundation of the theory of disk accretion on gravitating centers was laid by the present author under the guidance of Ya B. The publication was made in the Soviet periodical *Astronomisheskii Zhurnal* (*Astronomical Journal*) [20] in 1972. An experience I will never forget is the talk on the first Uhuru results which was given by the world-renowned scientist Jeffry Burbidge at FIAN in the summer of 1971. I had the opportunity to discuss with him these results and even to hand over to him a typewritten copy of my paper — something which, my colleagues told me, might get the professor into



N I Shakura (left) and R A Sunyaev in the early 1970s.

trouble when crossing the border in the airport. Luckily, it seems they proved to be wrong.

The bulk of the work was done together with Rashid Sunyaev. In another of our joint efforts, the so-called standard model of disk accretion was developed and worked out in detail, which was presented [21] at the 55th Symposium of the International Astronomical Union held in May 1972 in Madrid. The symposium covered not only data from Uhuru but also the first theoretical results on modeling the compact X-ray sources it detected in binary stellar systems, i.e., accreting black holes and neutron stars. Out joint work was presented by Jim Pringle (UK) — Rashid and I were then 'nevyezdnye' (not free to go abroad) — and was in fact an introduction to a large scale paper [22] which was later published in 1973 in the high-profile European journal *Astronomy and Astrophysics*, and on the basis of which Igor Novikov and Kip Thorne were able to calculate accurately the relativistic corrections to radiation due to general relativity effects near black holes [23].

The results Uhuru produced during its three years of operation were spectacular. Not only were a large number (339) of newly discovered X-ray sources catalogued, but Uhuru also provided guidance for other space observatories. Currently, space X-ray sources of various natures (not necessarily accreting relativistic stars in binary stellar systems!) number in the hundreds of thousands.

Rashid's and my pioneering paper [22] gained, and indeed still enjoys, wide popularity; its number of citations as of December 2013, i.e., forty years on, exceeding 6400.

The study of accretion disks has led to the discovery in the cores of active galaxies and in quasars of supermassive black holes with masses ranging from a few dozen to a few hundred millions solar masses. The first theoretical results on the glowing of accretion disks around supermassive black holes were published by David Lynden-Bell (UK) in 1969 in *Nature* [24]. The current state of research on the astrophysical aspects of black holes in binaries, especially in those in galactic cores and in quasars, is reviewed in the present *UFN* issue by A M Cherepashchuk [25] (see also Ref. [26]). The objective here was to highlight Ya B Zeldovich's central role in the study of the observational manifestations of black holes and in the development of the theory of disk accretion nearly half a century ago.

While we were still in our younger years, Ya B maintained extremely tight control over our work. As time went on, though, his interest turned to cosmology, a change which enriched this field with such jewels as Zeldovich's 'pancakes', the Sunyaev–Zeldovich effect, and the Zeldovich–Harrison spectrum. As a professor at MSU, he delivered two annual lecture courses for undergraduates and postgraduates: one on the structure and evolution of stars, and the other on cosmology. He took great care in preparing his lectures, his usual practice having been to write the text in a thin exercise-book, each year a new one. I was given the task of putting up announcements advertising his lectures. I attended many of his lectures, which resulted in the Zeldovich–Blinnikov–Shakura's manual, *Physical Foundations of the Structure and Evolution of Stars* (MSU Publishing, 1981). Another MSU publication in 1988 was the manual *Cosmology of the Early Universe* by Dolgov, Zeldovich, and Sazhin.

A few more episodes of, shall I say, a parascientific nature seem worth recounting. After one of his lectures, Ya B Zeldovich came up to me and asked me to do him a favor, which was to attach to his jacket three Hero of Socialist Labor (!) medals, which he pulled out of his back pocket, wrapped in cloth and all on the same strip of wood. My mind still with the lecture, I did the job rather absent-mindedly, the academician left the auditorium for some business of his, and I did not give any of this a second thought. Later on, I learned that these awards were the recognition of his participation in the Soviet Atomic Project — a period in his life he never spoke about, nor did I myself ask him for only too obvious reasons. Rumor had it that he only used his decorations when visiting high-rank offices — usually with no purpose other than to arrange things for young specialists.

One day I was out of time on my way to his lecture and was walking in a great hurry down the corridor toward the auditorium. A group of my fellow students stood before the auditorium looking at me with what seemed to me somewhat strange expressions on their faces. "Has he himself come yet?" — I asked them running and then, turning back, I saw the 'he himself', Ya B, following my footsteps, with his finger on his lips. After that, 'he himself' became his nickname for me, well consistent, in a sense, with his habit of always doing everything by himself, with others just being his co-authors. (*Translator's note*: This passage is admittedly an awkward attempt to translate an untranslatable Russian play on words.)

Yakov Borisovich Zeldovich died on 2 December 1987. He will always be dearly remembered by all those whom he taught the uneasy trade of how to be a scientist. "Do it like me, do it better than me" was his motto throughout his entire life. One of the twentieth century's great scientific geniuses, he was a towering figure of the epoch, carried away forever by the river of time. That was a contradictory and ambiguous epoch — but have there ever been great epochs and great men free of contradiction and ambiguity?

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