PERSONALIA

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In memory of Leonid Petrovich Grishchuk

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L P Grishchuk, expert in the theory of gravitation, cosmologist of world-renown, Professor at Sternberg Astronomical Institute, Moscow State University (GAISh), Professor at Cardiff University (UK), and member of the *Physics–Uspekhi* Editorial Board, died on 13 September 2012 after a brief, severe illness.

Leonid Petrovich Grishchuk was born on 16 August 1941 in Zhitomir (Ukraine); he was the youngest in a large family (with four older brothers and a sister). Having left secondary school with highest distinction (Gold Medal) in 1958, Grishchuk enrolled in the Department of Physics of Moscow State University (MSU), first in the physics division; but in the middle of his freshman year, he transferred to the division of astronomy, to which he remained faithful until his last days.

L P Grishchuk, a gifted mathematician, became fascinated with cosmological problems and prepared his diploma work under the supervision of Abram Leonidovich Zelmanov, a well-known cosmologist, who understood clearly that the then-available cosmological models were not accurate enough for describing the real Universe, because they did not take into account deviations from the homogeneous and isotropic distribution of cosmological matter. After graduation, L P Grishchuk became A L Zelmanov's postgraduate student, and after three years submitted his PhD thesis, "On the problem of singularities in the solutions of Einstein's equations," which he successfully defended in 1967. In fact, this was preceded by heated polemics with renowned Moscow physicists E M Lifshitz and I M Khalatnikov, who published important papers on the subject. The dispute was about the character and physical essence of singularities which emerged in the solutions of equations of general relativity. Leonid Petrovich was dealing with solutions of these equations for dusty matter (with initial conditions comprising rotation), which led to a physical peculiarity (singularity) characterized by both the density of matter and the curvature of space going to infinity. In addition, the thesis presented evidence that this singularity is, in fact, a caustic on a time-like hypersurface (a so-called 'naked' singularity). He also proved that each element of volume in such a caustic increases its density as its shape flattens and transforms into a pancake-like configuration — the effect that Ya B Zeldovich described some time later for the nonrelativistic case. Therefore, the theorem that Grishchuk proved in the thesis was the first constructive refutation of the statement that solutions of equations of general relativity (in a vacuum or in the presence of matter) cannot have a physical singularity. This theorem could lead to the conclusion that there is inevitability in how pancake-like objects may dictate the pattern of motion of matter during the

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post-recombination epoch in the evolution of the Universe. Such a conclusion proved to be very important for understanding the specific features of the formation of a large-scale structure of the Universe and, as a consequence, of galaxies too. In addition, his thesis also developed a theory of cosmological models that are homogeneous in the sense of the so-called Zelmanov's criterion (sometimes referred to in the literature as the Zelmanov–Grishchuk criterion).

Almost immediately after the *viva voce* of the thesis, L P Grishchuk was invited to join the University of Warsaw. One of the results of this collaboration was a paper (written jointly with well-known Polish cosmologist M Demianski) concerning rotation effects in the dynamics of a homogeneous, anisotropic Universe.

In the years that followed, Leonid Petrovich turned to the problems of gravitational radiation, sources of gravitational waves and their interaction with matter, fields, and quantum systems.

In the early 1970s, it was almost universally believed that the equations governing all fundamental physical fields are conformally invariant, and this implied that the rapidly expanding Universe could not create particles of any kind. L P Grishchuk was skeptical of this claim. From Einstein's field equations, he deduced the equation that governed gravitational waves in the early Universe, and showed that this equation *is not* conformally invariant. On this basis, he predicted that a rich spectrum of primordial gravitons should have emerged from the Big Bang. This had two major consequences. First, it triggered the observational search for evidence of primordial gravitational radiation (a search that has become the holy grail for modern cosmologists). Second, it broke the mistaken dogmatic mindset of cosmologists of the early 1970s, and forced them to accept that other particles could have been created, along with gravitons, by rapid (now called 'inflationary') expansion in the early Universe.

L P Grishchuk's other research on gravitational radiation and cosmology was strongly influenced by the concepts formulated by Ya B Zeldovich and his colleagues and postgraduate students, by physics colleagues abroad (first and foremost by Kip Thorne of Caltech (USA)), and by the staff of V B Braginsky's laboratory at the MSU Department of Physics. Together with his students, L P Grishchuk formulated a fundamental concept stating that quantum-mechanical generation of cosmological perturbations in the early Universe can be explained in terms of 'squeezed' quantum states which produce standing waves and modulate individual peaks in the power spectrum of fluctuations of the microwave background radiation (the so-called Sakharov oscillations). Later on, Grishchuk returned to this concept on several occasions and continued to disagree with most contemporary cosmologists in his interpretation of the nature of Sakharov oscillations; in May 2011, L P Grishchuk delivered a large invited talk about this problem to a conference at Lebedev Physical Institute, RAS devoted to the 90th anniversary of the birth of Andrei Sakharov (*Phys. Usp.* **55** 210 (2012)). Grishchuk's work of the 1970s (in collaboration with V B Braginsky, A G Doroshkevich, Ya B Zeldovich, I D Novikov, and M V Sazhin) on the theory of interaction between gravitational and electromagnetic waves was found essential for designing laser-type interferometric detectors (LIGO in the USA, VIRGO in Europe) and microwave cavities. In the 1980s, L P Grishchuk and his coauthors identified new physical effects due to gravitational waves: kinematic resonance, drift particle streams, and the memory of the position (with V B Braginsky) and the memory of the velocity (with A G Polnarev) of free particles after the passage of a gravitational wave. In this field, in 1977 Leonid Petrovich successfully submitted and defended at the GAISh the Habilitation thesis, "Gravitational waves, their physical properties and astrophysical manifestations".

In the years that followed, L P Grishchuk was able to show (in collaboration with M V Sazhin) that the sensitivity of gravitational wave detectors, like Weber's resonant cylinders, can be greatly amplified in the case of 'squeezed' quantum states through suppression of thermal noise. Later, it became possible to develop a more general quantum theory for detectors of this type. At the same time, L P Grishchuk and his postgraduate student S M Kopeikin obtained relativistic equations of the motion of compact bodies (neutron stars, black holes), taking into account the recoil accompanying their emission of gravitational waves.

Leonid Petrovich collaborated fruitfully with Ya B Zeldovich. This collaboration became especially close when, on L P Grishchuk's initiative, Zeldovich became Head of Relativistic Astrophysics Department at GAISh in 1982. L P Grishchuk and Ya B Zeldovich were able to show that the data on the magnitude of the quadrupole component in temperature fluctuations of the cosmic microwave background (CMB) radiation impose strong constraints on the magnitudes of homogeneity and anisotropy of the Universe on length scales hundreds of times greater than the current Hubble length (the Grishchuk–Zeldovich effect). L P Grishchuk, together with V A Belinskii, I M Khalatnikov, and Ya B Zeldovich, found the proof that 'inflationary trajectories' for a dynamical system that includes scalar and gravitational fields act as attractors for phase curves of this system. The work of L P Grishchuk and Ya B Zeldovich in relation to the possibility of the Universe emerging 'from nothing' was, to some extent, an anticipation of the inflationary models of the Universe, although in later years L P Grishchuk was rather sceptical about these models. L P Grishchuk, together with Ya B Zeldovich, wrote two reviews for the encyclopedia, *Physics of the Cosmos* (Moscow: Soviet Encyclopedia, 1976): "Gravitation" and "Cosmology", and two methodological notes for *Physics–Uspekhi* (1986, 1988).

It is only natural that, in his work on cosmology, Leonid Petrovich relied mostly on general relativity (GR) as the theory of gravitation that enjoys the highest prestige. Nevertheless, he never treated it as dogma that was solidified once and for all. He was always thinking about the foundations of the theory of gravitation and about GR's place among other physical theories. The result was a number of publications on the theory of gravitation. For instance, in 1990, L P Grishchuk and B Bertotti analyzed the strong equivalence principle and concluded that in GR, in contrast to other metric theories, this principle, under certain restrictions, exerts influence on the parameters of the system. An important segment of L P Grishchuk's output was in the so-called field formulation of general relativity on an arbitrary curved background, developed together with A N Petrov and A D Popova. It was created in the first half of the 1980s. The gist of the theory was that in this representation of general relativity all fields, including the gravitational field, propagate against the background of a given spacetime. Both formulations — the geometrical, and the field one — constituted two representations of one and the same theory, which gave identical results, with one of the two formulations gaining preference depending on the nature of the problem needing solution. Further progress of the theory showed that the field approach was very productive in the construction of conserved quantities in any metric and in multidimensional gravitation.

At the beginning of the 2000s, Leonid Petrovich, together with his postgraduate student S V Babak, proposed a variant of the massive theory of gravitation (a modification of GR) in which, in contrast to known similar theories, two types of gravitons possess mass: ordinary spin-2 gravitons, and scalar spin-0 gravitons. The foundation of this theory was the field formulation of GR against a flat background. The authors showed that, assuming a very low mass of gravitons, $m_0 = 10^{-65}$ g, their theory produced such objects as 'naked singularities' instead of ordinary classical black holes with event horizons, and that monotonic expansion of the Universe is replaced with an oscillatory process.

During 1990–1991, L P Grishchuk went to the University of Colorado at Boulder (USA) in the framework of a scientific exchange program, and in 1992–1993 — to Washington University in St. Louis (USA). At the same time, he actively collaborated with a group of gravitation experts at Caltech, led by Professor Kip Thorne, which at the time was laying the foundations for the four-kilometer-long Laser Interferometer

Gravitational Wave Observatory (LIGO). A decade later, Grishchuk pointed out and corrected an error in how the LIGO scientists were analyzing their data — an error that would have led to an incorrect interpretation of observations at the high-frequency end of the LIGO signal spectrum. Leonid Petrovich not only shared common research interests with Kip Thorne, but there also existed a sincere and deep friendship between the two, starting from the end of the 1960s.

Beginning in 1995, L P Grishchuk became a professor at Cardiff University (UK) and worked there until retiring in 2009; he continued working on his research projects until his untimely death. Leonid Petrovich also continued to be a professor at Moscow State University, where he had joint grants and coauthors. He would come to Moscow twice a year and actively discuss the hottest problems of astrophysics with Moscow colleagues.

He actively followed new observational data on binary black holes in galactic nuclei, regarding them as promising sources of gravitational waves. He mulled over the problem of gravitational lenses, especially in cases where such lenses are massive binary black holes residing in galactic nuclei. He immediately responded to discoveries of very distant galaxies and quasars, and thought about their possible ways of formation over a short cosmological time ($< 0.5 \times 10^9$ years). In 2006, Leonid Petrovich, along with A G Polnarev and D Baskaran, developed a new method of detecting cosmological gravitational waves using the correlation of the anisotropy and the E-polarization of the CMB radiation.

We are left with the painful regret that, alas, L P Grishchuk did not live long enough to witness the anticipated detection of gravitational waves with the LIGO interferometer; both he himself and his friend Kip Thorne firmly believed in the inevitability of this achievement. Likewise, Leonid Petrovich left us too early to be able to go through the published data from the PLANCK mission concerning the pattern of the power spectrum of temperature and polarization of the microwave radiation which would deviate — L P Grishchuk was absolutely sure — from predictions unless the considerable contribution of cosmological gravitational waves was taken into account (these results will only be published in mid 2013).

Some other ideas cherished by Leonid Petrovich are also left unimplemented. For example, he intended to write a book devoted to the problem of detecting gravitational waves and to searching for the most likely sources. He never completed the paper on gravitational-wave memory in the cosmological context. And he never developed the ideas that he had for how gravitational perturbations with wavelengths far larger than the Hubble scale might have been responsible for the observed accelerated expansion of the Universe. However, all important things considered, we can say that L P Grishchuk did succeed in expressing his points of view on the role of gravitational waves in cosmology, as well as his ideas on their possible observational consequences, in his numerous papers and talks to colleagues.

Leonid Petrovich was a passionate man. He loved life, he loved physics, he loved his family and friends. In physics, he never followed fashion. He probed issues for himself, in his own way, and often saw more deeply than many others. The bright memory of Leonid Petrovich Grishchuk will always warm the hearts of his friends and colleagues.

V B Braginsky, N S Kardashev, B V Komberg,
V G Kurt, I D Novikov, A G Polnarev,
K A Postnov, V A Rubakov, V N Rudenko,
K S Thorne, A M Cherepashchuk, N I Shakura