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Black hole physics

In the information "From Editorial Board" published in the first issue of Physics – Uspekhi **42** (*1999*) *it was noted that our journal will review foreign books "only in the cases when their content is closely linked with a development of physics in Russia". One could add that our journal will review also books published in foreign countries not in Russian but which were written by Soviet or Russian authors. Unfortunately, for pure technical reasons publications of these books in Russian now is very difficult, even if the books quite deserve issuing. The reviewed monograph by V P Frolov and I D Novikov serves as an example of such a kind. To translate the fundamental monograph into Russian and publish it here is evidently exhausting problem. Therefore, we present here the respective detailed review. To the point, the book authors did not break links with Russia and Russian science, in particular, they are preparing a comprehensive review for Physics – Uspekhi.*

From Editorial Board

V P Frolov, I D Novikov. *Black Hole Physics: Basic Concepts and New Developments* (Dordrecht, Boston, London: Kluwer Academic Publ., 1998) 770 pp.

"*... and where do such possibilities come from, if all we have are holes?!*"
Peter Weiss "The Persecution and Murder of Jean Paul Marat" (Epigraph to the Russian edition of the book "The Physics of Black Holes" [1])

"*I'm trying to understand...*
the black hole in the sky.
Why?...
It's another time,
It's another space..."
A Monn, A Lear "Black Holes"

At the end of 1998 the book *Black Hole Physics*: *Basic Concepts and New Developments* was published. The authors of this remarkable book — V P Frolov and I D Novikov — are outstanding physicists, our compatriots, now working abroad. There is no need of presentation of their names. Undoubtedly they are gems of the national science. Now V P Frolov is a professor at the University of Alberta (Edmonton, Canada), and I D Novikov is the director of the Theoretical Astrophysics Center in Copenhagen. Another time a description of their contribution to national science might be unnecessary, however, it so happened that a whole generation of young scientists, post-graduate and undergraduate students — who unfortunately did not have the opportunity to see and listen to either the lectures of these scientists or participate in discussions at their scientific seminars — has grown up in Russia. For the scientific youth I would like to say few words about my impression of 10 – 20 years ago.

Certainly to describe the influence of an outstanding person is as difficult as to describe a flavor, a color, a scent or a sound using only words. However, just as the black hole reveals itself through changing the properties of its environment, the reports and lectures of these scientists changed the state of the audience and roused an active interest in the subject discussed. Personally, I thank my fate for the possibility of discussing black hole physics with V P Frolov, I D Novikov and J A Wheeler. Undoubtedly, at the time V P Frolov was one of the most skilled and erudite experts in black hole theory, black hole thermodynamics and quantum processes near black holes in our country, whereas I D Novikov was a great expert in creating relativistic models in astrophysics. I would like to emphasize that I D Novikov is the most brilliant generator of new ideas, concepts and notions (for example, such a term — 'relativistic astrophysics' — appeared firstly as the title of a review in *Physics – Uspekhi* in 1964 [2] and as the title of the book [3] which was written by I D Novikov jointly with Ya B Zel'dovich). A convenient and successful name for a physical notion is of great importance for science development and even for the development of society as a whole. It might be proved by analyzing the influence on science development of such notions as 'dark matter', the 'Big Bang', the 'inflation model in cosmology' and, of course, a 'black hole'.

Three books on relativistic astrophysics [3 – 5] set down the basis for this part of science and became the foundation for further investigations not only in our country but abroad too since English translations of these books were published very soon after their Russian editions. To understand the really extraordinary contribution of I D Novikov to modern science we recall the title of one of the talk — NORA (Non-Ordinary Relativistic Astrophysics) — at the jubilee scientific conference in Copenhagen, devoted to his sixtieth birthday. Notice that the abbreviation of the talk title coincides fully — maybe accidentally or may be not — with the first name of his wife.

The development of black hole physics could be presented in the following periods: the prehistoric period starting from the discussion of this idea by Michell (it was Michell who received the letter from H Cavendish with the first derivation of the bending angle of a light ray in a gravitational field, and this essentially formed the basics of gravitational lens theory) and P Laplace (who considered the possibility of existence of such objects in the Newtonian theory of gravity at the end of the XVIII century) and finishing in 1916 when K Schwarzschild published his solution of the Einstein equations [the solution describes a static (nonrotational) black hole]; the ancient history period starting in 1916 and finishing on 29 December 1967, when the famous American scientist J A Wheeler first introduced the term 'black hole' in his lecture presented at the Hilton hotel in New York (at the end of this period in 1963, the Australian mathematician R P Kerr found the vacuum solution of the Einstein equations, which describes a

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Translated by A F Zakharov

rotating black hole). From this Wheeler lecture a period of new history started — the 'youth' of this new field of physics (according to the authors of the book, the 'heroic era of development of black hole physics'). This period is characterized by a rapid growth of investigations and finished in 1986 with the first publication of *The Physics of Black Holes* by I D Novikov and V P Frolov (notice that at the same time were published an informative monograph by D V Gal'tsov [6], an original English edition of the collective monograph by K Thorne, R Price, and D Macdonald [7] — where a membrane paradigm in black hole physics is presented — which was translated into Russian in 1988, and also a Russian translation of a remarkable monograph by S Chandrasekhar [8] published in English in 1983).

The modern era of black hole physics — from 1986 up to the present day — is a period of marvelous success in studying theoretical and mathematical aspects of the theory of black holes. But it is the discovery of compact objects in several stellar binaries, which in the words of the authors "almost one hundred per cent should be black holes", that is most important. Besides, intensive research of active galactic nuclei being carried out in various spectral ranges leads to the necessity of existence of supermassive black holes with masses of a few million solar masses.

With hindsight of the more than thirty-year history of the term 'black hole', we now see that it was this notion that became a new paradigm contributing to the intensive development of relativistic astrophysics. Comparing this notion with the terms used earlier such as 'frozen star' or 'collapsar', we can see how the application of the latter could have limited the study of black holes. For instance, this would make the study of physical processes in horizon surroundings more difficult, moreover it would be impossible to formulate statements on processes inside the black hole horizon.

One may say — using a mathematical analogy — that the use of the term 'black hole' instead of 'collapsar' is the same as using an actual infinity instead of a divergent sequence (or an actual infinitesimal instead of a sequence convergent to zero). These mathematical notions (of infinitely larges and infinitesimals) earlier used by such classicists of science as G W Leibniz and L Euler, were introduced once again in mathematics a few dozen years ago at a necessary level of rigor and became the basis of so-called nonstandard mathematical analysis, where a lot of theorem proofs realized with actual infinities and infinitesimals and believed to be not rigorous enough got the necessary mathematical rigor. Thus, such a notion as an 'actual infinity' (or an 'actual infinitesimal') is a key paradigm in the nonstandard analysis and makes possible a fresh look at the 'standard' mathematical analysis.

Just like this paradigm in the mathematical analysis such a notion as a 'black hole' is one of key notions in relativistic astrophysics. It is obvious that a scientific notion must precisely describe the nature of an analyzed object; at the same time it should have some internal magnetic force which can engage the interest of wide circles of society (along with black holes we could recall such notions as the principle of relativity, dark matter, the inflation model, etc.).

Really, in the late 1960s black holes transformed from the subject of studies of only experts on general relativity (at this time, according to the authors, astronomers were very far from consideration of black holes and even discussions on this were not welcome in 'respectable society') to a subject of everyday studies of astronomers and astrophysicists [to make sure, one can have a look at volumes of *The Astrophysical Journal*, Russian *Astronomy Reports* or the electronic library of preprints at LANL (Los Alamos National Laboratory)]. The term 'black hole' became sufficiently ingrained in the social consciousness too, consequently it is hardly probable to find another astronomical notion (all the more, a notion in general relativity) which is so well-known even in wide circles very far from astronomy and general relativity.

Apparently a black hole is the most perfect object in nature, since it is characterized by only three numbers: its mass, angular momentum and charge. Wheeler expressed this statement as the hypothesis — "Black holes have no hair". Later, this statement was proved for stationary black holes, namely, in the general case a stationary black hole is described by the Kerr – Newman metric. It is considered that even in the case when a formed black hole was not stationary, it loses all distinguishing characteristics by radiation and thus becomes stationary. Therefore, a stationary black hole is a general case of a black hole to a large extent, so the Wheeler statement is substantially applicable to all black holes.

According to the authors, the book presents an introduction to black hole physics and gives a description of methods used in the scientific field. In the book the main attention is devoted to results obtained recently and thus not sufficiently presented in other books and reviews. More details on fairly ordinary items of the theory, which can be found in other books and reviews, are briefly discussed. The book is addressed to a wide circle of physicists and astrophysicists who have no special knowledge of black hole physics.

The authors place the emphasis on explanation of the physical nature of the considered effects and only after that the mathematical constructions required for their study are shown. Besides, the authors stress that they have consciously avoided excessive complexity in formulations and proofs of theorems on black holes. The major ideas are given very often instead of full proofs, then the main stages of proofs are introduced and only after that the references to original papers are presented, where one could find all the necessary details.

In the context, the reviewed book is cardinally different from the monograph by S Chandrasekhar [8], where full proofs are presented for all statements considered in the book (however, a reader should insert at times a few dozen lines between those of Chandrasekhar's book for a full understanding). Therefore, the book by Chandrasekhar is a sample of a most precise description of black hole theory, whereas the reviewed book is a sample of a most full presentation. It is necessary to note that the title of Chandrasekhar's book is *Mathematical Theory ...*, but the reviewed book is *... Physics*, to understand which emphasis was placed by the authors of these two remarkable monographs.

The period after the publication of the first edition of the book *The Physics of Black Holes* by I D Novikov and V P Frolov in 1986 could be characterized as the period of 'storm and onslaught' and as a result great progress in the black hole theory was made, therefore the reviewed (second) edition differs from the first by no means only in 'cosmetic' improvements. Really it is a new book, larger than the first edition by two times and containing a lot of new information and data. The description structure and most of the content of the first edition of the book are kept in the second edition. However, each section contains essential additions and new sections have appeared in the second edition; thus the book presents a detailed description of the modern state of black hole physics.

The reviewed book is divided into two parts. Part I "Basic Concepts", where the 'classical' theory of black holes is presented, contains nine chapters: Introduction; a Brief History of Black Hole Physics; Spherically Symmetric Black Holes; Rotating Black Holes; Black Hole Perturbations; General Properties of Black Holes; Stationary Black Holes; Physical Effects in the Gravitational Field of a Black Hole; Black Hole Electrodynamics, and Astrophysics of Black Holes.

Part II "Further Developments" is devoted to more complicated constructions connected with black holes and contains seven chapters: Quantum Particle Creation by Black Holes; Quantum Physics of Black Holes; Thermodynamics of Black Holes; Black Holes in Unified Theories; The Interior of a Black Hole; Ultimate Fate of Black and White Holes, and Black Holes, Wormholes and Time Machines.

Most of the technical details and cumbersome expressions are put in appendices, of which there are nine instead of the one in the first edition. The total size of the appendices increased from eight pages in the first edition to about a hundred pages in the reviewed book. Thus, one can consider the appendices to be a separate reference book containing the basic expressions and notions of general relativity and black hole theory. Appendix A "Mathematical Formulas" contains the central formulas of Riemann geometry and the appendix could be regarded as an extended version of the one in the first edition. Besides, there are the following: Spherically Symmetric Spacetimes; Rindler Frames in Minkowski Spacetime; Kerr–Newman Geometry; Newman–Penrose Formalism; Wave Fields in Curved Spacetime; Wave Fields in a Kerr Metric; Quantum Fields in Kerr Spacetime, and Quantum Oscillator.

Each chapter of the new book has become more informative (than the respective chapter of the first edition) and twice longer; however, on the whole, the general structure of the book has been preserved. We point out some changes of the book structure which have been appeared in the second edition.

Thus, the content of Chapter 3 "Wave Fields around a Spherically Symmetric Black Hole" in the first edition of the book has been placed into Chapter 4 "Black Hole Perturbations" of the second edition, which is expanded by the addition of the following important sections: "Quasi-normal Modes", "Power-Law Tails", "Wave Fields around a Rotating Black Hole", "Stability of Black Holes", and "Gravitational Waves from Binary Systems".

The new Chapter 9 "Astrophysics of Black Holes" was added into part I of the reviewed book. This chapter seems to be the most important, giving us a presentation of the fact that such a purely theoretical concept as the black hole has changed into an object of everyday astrophysical and astronomical investigations (a reader can get a notion how many new interesting results have been obtained in recent years, if he compares the content of this chapter with older reviews [9, 10] which have the same title as Chapter 9 of the reviewed book and with the respective chapters of the monograph by Shapiro and Teukolsky [11]). Besides an Introduction this chapter contains the following sections: "The Origin of Stellar Black Holes"; "Stellar Black Holes in the Interstellar Medium"; "Disk Accretion onto Black Holes"; "Evidence for Black Holes in Stellar Binary Systems"; "Supermassive Black Holes in Galactic Centers"; "Dynamical Evidence for Black Holes in Galactic Nuclei"; "Primordial Black Holes", and "Black Holes and Gravitational Wave Astronomy".

Let us consider briefly the content of these sections. The recent theoretical estimates for the maximal mass of a neutron star as $(2-3) \times M_{\odot}$ (for a neutron star without rotation) and smaller than $M_0 \approx 3M_{\odot}$ (for a neutron star with rotation) are presented in the section "The Origin of Stellar Black Holes". However, the mass estimates for compact companions in ten binary systems, cited in the section "Evidence for Black Holes in Stellar Binary Systems", significantly exceed the limit mass of a neutron star and from this it was concluded that black holes exist in these binary systems. The arguments for black hole existence could be more convincing if the authors presented not only estimates for the compact object mass, but also estimates of the mass functions for these binary systems, which were given in a recent review by A M Cherepashchuk [12]. Recall that the mass function gives us the minimal value of the mass of a compact companion (independently from the ratio of component masses and the inclination angle for their orbits) and for six binary systems the mass functions are greater than $3 \times M_{\odot}$, whereas for three significantly greater, so for the binary systems GS 2023 + 338 (V404 Cyg), GS 2000 + 25(QZ Vul) and XN Oph 1977 the mass functions are 6.3, 5 and 4 solar masses, correspondingly [12]. In this case if we think that general relativity correctly describes a strong gravitational field, we must inevitably identify these compact objects as black holes. For this reason, the authors of the reviewed book conclude that "such objects should be black holes almost one hundred per cent".

In the section "Dynamical Evidence for Black Holes in Galactic Nuclei", the possibility of existence of supermassive black holes not only in active galactic nuclei but also in nuclei of 'normal' galaxies, like our Galaxy, are considered. In that case, the story has been somewhat similar to the case of establishing the existence of black holes with stellar masses. Namely, a source can be identified as black hole if there is proof of the existence of enough dark mass in a small volume, so this object cannot be something other than a black hole. Such proof for the existence of supermassive black holes is based on studying stellar kinematics and the photometry of galactic nuclei. Using these data, the mass of the black hole in our Galaxy is estimated as $3 \times 10^6 M_{\odot}$, for galaxy M87 — $2.4 \times 10^9 M_{\odot}$, for galaxies NGC 4594 and NGC 3115 — $10^9 M_{\odot}$. A detailed description of observational indications of galactic black holes and appropriate theoretical models can be found in the review by Liang [13], where difficulties in interpretation of some observational data are also considered. One could find a description of modern results connected with black hole searches in the recent popular paper by Blandford and Gehrels [14]. The section "Black Holes and Gravitational Wave Astronomy" written jointly with N Andersson finishes Chapter 9. This section is also very important and interesting, so it remains to regret that the volume of the section is only four pages, since in the next millennium very large gravitational wave detectors (laser interferometers) will be operating: the American LIGO, the French–Italian VIRGO, the German–British GEO, the Japanese TAMA, and the Australian AIGO; binary black holes are probably the most perspective sources of gravitational radiation.

Based on calculations of binary stellar system evolution, one could conclude that in spite of binary black hole systems occuring more rarely than binary neutron star systems, binary black holes are essentially more powerful sources of gravitational radiation, so perhaps it could be probable to detect a gravitational wave signal from binary black holes. A reader can familiarize himself with publications on the subject using references from the comprehensive reviews by K S Thorne referenced in the book.

Chapter 10 "Quantum Particle Creation by Black Holes" contains a treatment of such an important phenomenon as their 'evaporation' discovered by S Hawking, which significantly 'refreshed' our understanding of black holes.

Chapter 10 "Vacuum Polarization in Black Holes" of the first (Russian) edition is involved as a small part in Chapter 11 "Quantum Physics of Black Holes" of the second reviewed edition. Chapter 11 also contains such an important section as "Quantum Mechanics of Black Holes".

In the reviewed edition a new Chapter 13 "Black Holes in Unified Theories" was added, where partially dilaton black holes, colored black holes which could have Abelian and non-Abelian 'hairs' are considered, namely, those black hole type solutions which may be obtained in theories unifying gravity with other gauge fields. Moreover, the stability of such black holes was discussed. Cases where black holes may have quantum hair, including color and axion hairs, are treated as well.

A new chapter "Black Holes, Wormholes and Time Machines" was included in the second edition under review. The subject caused very wide public interest. The treatment of a 'time machine' in the vicinity of rotating black holes having a super-extreme rotation and forming so-called 'naked singularities' started more than twenty years ago. But there is a lot of objections against such constructions, for example, they are prohibited by the 'principle of cosmic censorship' (proposed by R Penrose) stating that singularities could be located inside horizons. K Thorne and his coauthors M Morris and U Yurtsever have considered another possibility for a time machine with a wormhole as an essential component of the construction [15]. According to a legend, the original version of their paper was presented for publication to the journal *Phys. Rev. Lett.*; it did not include K Thorne as a coauthor and received negative review from the referee perhaps because the subject was very unusual for such a serious scientific journal. But the paper was published after including K Thorne in the list of authors and caused wide scientific and public interest. A number of interesting and original time machines were 'built' jointly by the authors of the book reviewed and in collaboration with other researchers. V P Frolov talked about one such time machine at the conference on gravity in Portugal in 1993. After his talk a documentary film was shown on Portugal TV where it was reported that the long-term dream of mankind had come true and the object of discussions of Leonardo da Vinci and A Einstein had been realized, namely, scientists reported at the conference in Portugal that they knew how to build a time machine. In this film they showed not V P Frolov (who presented a unique report about time machines) but A Ashtekar who presented a talk about his original approach to quantum gravity (because, probably, this American scientist of Indian origin looked the most imposing from all the conference participants). After the showing of this film on Portugal TV, a correspondent of one of the Portugal newspapers asked V P Frolov to demonstrate the time machine in a hotel. V P Frolov explained patiently for a long time that only the theoretical possibility had been analyzed and a practical realization of these theoretical considerations is very far away, but the correspondent thought that the author in the usual manner did not want to demonstrate his 'invention'. Another very interesting film about time machines was shown by French TV. Explanations about this subject were given by such famous scientists as I D Novikov, K S Thorne and others. No doubt that research on the subject is very interesting not only for a wide circle of physicists and astronomers. One could gain an impression about this topical problem by reading the last chapter of the reviewed monograph.

The authors of the reviewed book wrote that they were restricted in the book's preparation "in time and space". Of course, it is very difficult to imagine some field of human activity which is not restricted either in time or in space but if we use scales of a human life, we conclude that the authors were practically unrestricted in space, since the ideas of black hole physics were considered by them at very different points of the Earth, and the authors were not restricted in time, since they exhibited their work on different problems of black hole physics over more than thirty years. The authors did a colossal work and the book published is unrivaled in the subject. The authors wrote that they have scientific sympathies and partialities which may not coincide with reader sympathies. No doubt, the review author has his partialities too. Therefore, using the opportunity I would like to point out a detail of the description of one aspect of the classical theory of black holes. So, in the section "Gravitational Capture" of Chapter 2 "Spherically Symmetric Black Holes" it would be expedient to present not only two limiting expressions for the capture cross-section of slow particles and the cross-section of ultra-relativistic particles, but also the general expression for the capture cross-section of a particle having arbitrary velocity at infinity (a clear derivation of the expression may be found in paper [16] and a generalization of such an approach is given in article [17]). In Chapter 3 "Rotating Black Holes" unfortunately an interesting paper [18] was not cited, where the behavior of potentials in a Kerr metric was considered and analytical expressions for parameters of spherical type orbits, which generalize known expressions for parameters of circular equatorial orbits, were derived.

Of course, in the time of realization of such a great work as a fundamental book, inevitably some small misprints appeared. However, it is regrettable when misprints have crept into the names of authors who made an essential contribution to the development of black hole physics. So, for example, the name of A M Khokhlov on page 732 was incorrectly shown with the references, where it was given as V P Frolov, A M Khlopov, I D Novikov, C J Petchik instead of V P Frolov, A M Khokhlov, I D Novikov, C J Petchik, thus the contribution of A M Khokhlov who is a known expert on applications of numerical methods of hydrodynamics to astrophysical problems was lost. On page 276 in two lines the name of a well-known Indian expert on gravity was incorrectly printed (it was erroneously given as Dadlich instead of Dadhich but was correctly printed in the references). The misprints are undeniably secondary.

The reviewed book gives us beyond any doubt the fullest description of the modern status of black hole physics and the possibility to call it the *Black Hole Encyclopedia*.

The review might be finished with words given in the introduction to a national textbook and seen by the review author about two dozen years ago, namely: "Let it be a useful book for our ... youth'', but it is clear that the book is quite expensive now for Russians and therefore the book is inaccessible not only to students, post-graduate students and researchers working in black hole physics and relativistic astrophysics, but also to major scientific libraries. Thus, a translation of this book into Russian could make an accessible 'window' for national researchers into black hole physics.

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