O‘ZBEKISTON FANLAR AKADEMIYASI
ULUG‘BEK NOMIDAGI
ASTRONOMIYA INSTITUTI

100052, Toshkent sh.
Astronomiya ko‘ch., 33-uy
Tel: (+99871) 2358102
Faks: (+99871) 2344867
E-manzil: info@astrin.uz
Veb: http://www.astrin.uz

ULUGH BEG ASTRONOMICAL
INSTITUTE OF THE UZBEKISTAN
ACADEMY OF SCIENCES

33, Astronomy St.,
Tashkent, 100052, Uzbekistan
Tel: (+99871) 2358102
Fax: (+99871) 2344867
E-mail: info@astrin.uz
Web: http://www.astrin.uz

№ _____ «_10__» ___May_____ 2018

R E P O R T

of the opponent on habilitation dissertation of Dr Jırı Kovar entitled ‘Charged fluids encircling compact objects: ‘Astrophysical levitation’’, presented for the scientific title of docent (Associate Professor) on Relativistic Astrophysics and Theoretical Physics

Electromagnetic fields play crucial role in the life history of majority astrophysical objects and their observable rich phenomenology is related to the existence of the electromagnetic radiation from them. Magnetic fields play also an important role in extracting the rotational energy of the black hole and its transformation into the electromagnetic radiation and the kinetic energy of the accelerated particles. Such relativistic high-energy astrophysical processes have been actually observed, but the area of origin remains below the resolution of modern telescopes. However Very Long Baseline Interferometry (VLBI) has already started to resolve microstructures around supermassive black holes (SMBH) which are connected to the magnetic fields existing in SMBH environment. It is assumed and believed that the high-energy processes near the center of the black holes can be described by the energy extraction of BHs through magnetic fields participation. Therefore, study of the particles, fluids and fields in the vicinity of black holes in the presence of electromagnetic fields is extremely important task related to the astrophysical and astronomical observations. The main reason for the study of electrodynamics of rotating black holes described by the Kerr solution is to explain their energetics which increases the interest to the study of the effects associated with the motion of particles and fluid near a rotating black hole in the presence of electromagnetic field. Thus, the **novelty and relevance** of the habilitation thesis topic **is not in doubt**.

The habilitation thesis represents the detailed description of the theoretical results published by the author in the serie of **eleven scientific papers** devoted to the theoretical modeling of electrically charged fluid structures circling close to compact gravitational objects, such as black holes and neutron stars. In particular the habilitation thesis reports unique theoretically found structures, the so-called levitating tori (toroidal structures centered above or under equatorial plane) around gravitational compact objects. Such an off-equatorial motion can occur due to the presence of electric charge distributed throughout the circling fluid, thus interacting with the background electromagnetic field.

The author develops **two different conceptions** of the charged fluid. The **first one** corresponds to an extremely diluted pressure-less fluid treated within the test-particles approximation, which can be considered as a kind of preliminary zero approximation study of the charged fluid motion. In particular, the author has performed the study of the charged test particles levitation in general relativity devoted to the existence and properties of the so-called halo orbits (stable circular trajectories with fixed non-equatorial latitudes) and related trapped off-equatorial trajectories in various background fields, which perfectly fits to isolated tiny charged corpuscles. However, such a study also provides very useful intuition for understanding the collective bulk motion of a more general charged fluid in the given background.

The **second conception** of the charged fluid developed by the author corresponds to the more general fluid, which is relatively dense, compressible and treated magneto-hydrodynamically. The general relativistic model for the charged fluid circling in different background fields developed shows that, as extension of the results of the test-particles approximation survey, under specific conditions, the fluid can soar up the equatorial plane and form the levitating torus. Moreover, the rotating charged fluid can also form, the so-called double torus (toroidal structure with two pseudo-centers) or polar cloud (structure centered on the symmetry axis). Some of these structures can be also constructed within the classical (weak-field) magneto-hydrodynamic approximation, even enhanced with an inclusion of self-gravity or within the kinetic theory approach.

Investigation of fluids under astrophysical conditions represents one of the most challenging tasks in physics. Encircling sources of strong gravity – compact objects, such as black holes and neutron stars, astrophysical fluids manifest typically as compressible (gaseous) fluids. One can find them in the form of pure neutral or quasineutral ionized gas (plasma), neutral or charged microscopic dust, dust grains (pressure-less fluid) and very often as a dispersed medium, such as dusty (grain) gas, dusty plasma, etc. The gaseous fluids can range from extremely diluted ones (represented by separated particles and well described within the test-particles approach), through diluted ones (described within the kinetic approach), up to the dense fluids (conveniently studied within the magneto-hydrodynamic approach). Astrophysical fluids can whirl in extremely complex dynamical situations. For instance, the fluids can fall down onto compact objects within accretion processes, be launched in the form of winds or jets, or settle down and form circling equilibrium configurations and based on this scenario the author has studied the accretion discs and related processes. Dr Jirı Kovar has numerically simulated and analytically constructed equilibrium configurations of the circling fluids which represent theoretical models of the accretion discs with negligible loss of mass. The data from X-ray astronomical observations, together with the theoretical models developed by the author, can provide probes for evidences of these discs and their physical characteristics. From the theoretical point of view, the equilibrium configurations of fluids circling around compact objects and taking toroidal forms represent unique structures exhibiting interplay of physical phenomena in extreme conditions. The effect of the gravity and electromagnetism should be strongest in the astrophysical processes occurring in the close vicinity of massive black holes and naked singularities in the strong field regime and can be recorded from the observations of the related astrophysical phenomena. The author is underlining that the gravity and electromagnetism around common astrophysical objects can represent the key factors in shaping the astrophysical fluids, predominantly governing their motion.

The habilitation dissertation of Dr Jirı Kovar consists of four chapters, representing the commentary on the serie of eleven scientific papers, appended as the second – supplementary part. The first chapter called **Introduction** with two sections **Inquiring test particles levitation** and **Inquiring fluid levitation** brings a motivation for the presented study and on a qualitative level, readers become familiar with the conception of investigated issues, main terms and with the most important results. By means of couple of illustrative and exemplary figures, this chapter represents an introduction to the habilitation thesis, however, it can be supposed as an independent comprehensive summary as well. The chapter also contains most of the citations to related studies.

The second and third chapters **Charged test particles Hamiltonian circling** and **Charged fluid magneto-hydrodynamic circling** represent main chapters of the thesis. They describe physical aspects and applied general relativistic formalisms. Especially, those concerning the dense compressible charged fluid should be emphasized nowadays. To demonstrate procedures of the formalisms, two representative scenarios are presented here: circulation of charged test particles in the rotating Kerr spacetime with accompanying test electric and asymptotically uniform magnetic fields and circulation of charged dense compressible fluid treated magneto-hydrodynamically in the Schwarzschild spacetime with

accompanying test dipole magnetic field. For convenience, even it is united throughout all the habilitation thesis, the most important notation is reminded in both the chapters, which can be read independently.

The fourth chapter **Conclusions** and discussion briefly summarizes presented investigation and points out challenges for further studies, being mainly aimed at the magneto-hydrodynamic model of the circling dense charged fluid. This chapter concludes the first part of the thesis, being followed by the second part with no chapters, containing only the published versions of all the commented papers.

The habilitation dissertation of Dr Jirı Kovar is devoted to the search for theoretical existence of intriguing structures, where the presence of electric charge and magnetic field play their essential roles. It has been performed the study of the electromagnetic field and the charged particles motion in the vicinity of rotating black hole immersed in an external magnetic field. The author has also shown that the charged equatorial tori and polar clouds can exist with relatively feasible physical characteristics, such as pressure, rest-mass density, charge density and temperature. For this purpose, he has fixed the background fields and fluid parameters so that the characteristics of the modeled structures did not deviate from the generally accepted limits for real fluid and, simultaneously, did not violate restrictions following from the approximations used in the model. The author has shown that the topology and physical characteristics of the studied structures strongly depend on the strength of the background electromagnetic fields into which the structures are immersed. Due to the self-consistency, as the charge throughout the constructed structures must be kept small, there was the ‘demand for’ strong electromagnetic fields in order to preserve the sufficient electromagnetic interaction. It seems the dipole-type magnetic fields of magnetized neutron stars, provide more or less sufficient fields.

Another interesting task of the habilitation dissertation is to determine the influence of magnetic field on the charged fluid circling around the idealized slowly rotating magnetized neutron star with its background fields approximated by the Schwarzschild spacetime with accompanying static test dipole magnetic field. By introducing another couple of transformations, the author has defined a kind of total potential – the direct generalization of the one used for the neutral fluid, with its equipotential surfaces mapping possible shapes of the fluid structures. He updated the mathematical concept for solving the pressure equations of the model, coupling them into one in integral form, which can be solved analytically. Bringing the charged fluid into this last kind of background, he has found that the revealed toroidal structures can take shapes from rich topological family. Rotating with constant specific angular momentum profile or with constant angular velocity, the toroidal structures exist not only in the equatorial plane as a single tori, but also as two coupled tori or even those joint as the so-called double para-equatorial tori. The author has also found that the toroidal structures can be formed out of the equatorial plane as a pair of separated levitating tori or joint as the so-called double off-equatorial tori. Along with the pure topological study of the possible toroidal variants by means of the equipotential surfaces, he also went through a basic astrophysical contextualization. By fitting the fluid and background fields parameters, he has proved that the toroidal structures can exist also within general physical limits given by the maximal central pressure, rest-mass density and temperature.

The dissertation work is a **complete survey**. The scientific results presented for the habilitation defense are **completely new and original**. The main results of the dissertation have been widely presented at the seminars and international conferences and have been extensively published in the leading international refereed journals. Numerous research papers published by the author and associated with presented habilitation thesis correctly reflect the content of the dissertation.

Reliability of the research results is provided by use of modern methods of general relativity, theory of electromagnetism, hydrodynamics and the theoretical physics and highly effective analytical and numerical methods and algorithms; it has been performed careful

comparison of a consistence of the obtained theoretical results with observational data and the relevant results obtained by other authors; conclusions are well consistent with the main provisions of the field theory of gravitational compact objects.

The disadvantage of the dissertation is the presence of a certain number of stylistic errors and typos. From point of view of the content it seems the author did not supply enough realistic estimations of magnetic fields around black holes under various conditions and information about the modern ways of their measurements and detection. From point of view of the research as the author is discussing in the habilitation thesis the correction to the equation of state due to the background electromagnetic field could be significant but not included, in addition as the author mentions their specific charges are extremely high to form fluid torus with negligible self-field. The author did not study the dependence of his results for the various magnetic field configurations in the black hole environment. However these important issues can be studied in the future research by the author. In general, these small shortcomings can not affect the assessment of **the high scientific value of the results** presented.

The **scientific and practical significance** of the thesis is determined by the ability of the developed formalism in the dissertation to analyze the various observational properties of gravitational compact objects to be obtained by a new generation of radiotelescopes in the millimeter diapason in the near future, and get an information on the various parameters and properties of the supermassive black holes at the center of our galaxy and galaxy M87. Moreover, the results of research can be used to obtain estimates of different parameters of black holes such as rotation and other parameters from X-ray binaries. Results can also be useful for the analysis of the nature and dynamics of the gravitational field, in the development of observational experiments and criteria for the detection and identification of the gravitational objects and structures around them. Thus, the habilitation dissertation is performed at a high scientific level and the results can be described as a big scientific achievement.

In the habilitation thesis astrophysical phenomena connected to astrophysical processes arising around black holes and neutron stars governed by general relativity are studied. A variety of relevant effects has been treated by Dr Jirı Kovar and the numerous effects predicted by the author will be in principle observable in the very near future due to an enormously fast development of observational techniques, for example, by EHT (Event Horizon Telescope), and could be confirmed helping in deeper understanding of the dynamics and flows around black holes. In order to find out which of the proposed theories can be taken seriously, one has to compare the predictions made by the author with observations of astrophysical objects where the presence of black holes could be expected. The information about the phenomena taking place in strong gravity astrophysical systems can be acquired from the electromagnetic radiation of a source being either a part of the strong gravity astrophysical system (e.g. the accretion disc), or can be far from the system of interest, but the source’s radiation that we detect is influenced by the gravitational effects of the strong gravity and electromagnetism system which are extensively studied in the habilitation dissertation. Overall I would say that the author has made very important and significant contributions to the black hole astrophysics which would soon reach threshold of observational verification.

I personally know Dr Jirı Kovar since several last years from my visits to the Czech Republic where I have been invited as participant of the workshops and as short-term visiting professor. From my stays and visits to the Czech Republic I can strongly confirm that he is one of the leading teachers at the faculty, leaded by Professor Zdenek Stuchlik, who provides the students with a high quality supervision and lecturing for Master and Bachelor studies. Dr Jirı Kovar is the recognized specialist and expert on Black Holes, Exact and Numerical Solutions, Black Hole Electrodynamics, Mathematical Physics, Hydrodynamics Relativistic Stars, General Relativity etc. The applicant is hard working researcher and at this stage produced good number of papers published in the highly refereed journals. In additional he has made the numerous talks at the international conferences. I can confirm the high level of Dr Jirı Kovar's abilities to carry

out research at the high level. I also know him as a communicative and a tactful person with very strong mathematical background with good knowledge of theoretical physics.

Based on above written I am happy to underline that the habilitation dissertation ‘Charged fluids encircling compact objects: ‘Astrophysical levitation’’ meets all the requirements of the regulations on the procedure for the award of scientific titles in the Czech Republic and may be definitely admitted to the defense at the Silesian University in Opava and the author, Dr Jirı Kovar certainly deserves the award of the scientific title of Docent (Associate Professor).

ЎзР ФА Астрономия институтининг
бўлим мудири ф.-м.ф.д., проф. Б.Ж. Ахмедов

The referee report has been composed by
Professor, Dr.Sc. Bobomurat Ahmedov
Head, Theoretical Astrophysics Department
Ulugh Beg Astronomical Institute, Astronomicheskaya 33
Uzbekistan Academy of Sciences
Tashkent 100052, Uzbekistan
E-mail: ahmedov@astrin.uz
Phone: +998-71-2358102(home)/2355786(office)/+998977088068 (mob)