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R E P O R T

of the opponent on habilitation dissertation of Dr Jan Schee entitled ‘Optical phenomena probing the gravitational field of compact objects governed by alternative theories of gravity’, presented for the scientific title of docent (Associate Professor) on Relativistic Astrophysics and Theoretical Physics

Taking into account that the signatures of the general relativity, the quantum gravity, or alternate gravity theories, should be strongest in the astrophysical processes occurring in the close vicinity of massive black holes and naked singularities or their analogous related to the modifications or extensions of general relativity and can be decoded from the observations of the related optical phenomena the author in the habilitation thesis presents the results of his extensive theoretical studies related to optical phenomena connected to astrophysical processes arising around black holes and naked singularities governed by general relativity and most interesting and astrophysically relevant alternate gravity theories, or candidates of quantum gravity theory. A variety of relevant optical effects has been treated by Dr Jan Schee: construction of black hole shadow, gravitational lensing of light, optical appearance of accretion discs, profiled spectral lines of accretion Keplerian discs or accretion tori. 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 signatures of modifications of general relativity which could be confirmed, restricted, or excluded, helping in deeper understanding of the fundamental physical laws. 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 black holes (naked singularities, or so called superspinars) 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 lensing effects of the strong gravity system which are extensively studied in the habilitation dissertation.

The habilitation dissertation of Dr Jan Schee starts from the **Introduction** where he underlines the results of his important research on the imprints of the strong gravitational fields of black holes or superspinars (naked singularities), constructed in the framework of general relativity (GR) or proposed alternative theories of gravity for a variety of fundamental optical phenomena. It is related to the problem to probe the large number of alternative theories of gravity, as f(R) or f(T) theories, the rainbow gravity, conformal gravity, or higher dimensional gravity theories of the Lovelock type. The author summarizes that in the habilitation thesis main attention is focused on optical properties of the braneworld black holes and naked singularities, Horava gravity black holes and naked singularities, and regular black hole or no-horizon spacetimes being solutions of GR combined with non-linear electrodynamics.

The next section entitled **Theories of Gravity** is devoted to the review of various theories of gravity including General Relativity (GR), GR combined with non-linear electrodynamics, Regular Bardeen and ABG spacetimes, Braneworld models, Reissner-Nordstrom braneworld geometry, Kerr-Newman braneworld geometry, Horava gravity, Kehagias-Sfetsos geometry which I find very useful and informative.

In the section **Photons as Spacetime Probes** the author summarizes the crucial notions of the theory of optical effects in strong gravity and defines the local escape cones for photons related to fundamental families of observers, the related silhouette of black holes, frequency shift of radiated photons, and gravitational lensing focusing the incoming light. Then he discusses appearance of accretion configurations, spectral line profiles and light curves of hot spots on the accretion discs. This section consists of the following subsections: Equations of motion, GR framework, GR coupled to non-linear electrodynamics, Photon escape cones, Photon circular orbits, Light Escape Cone (LEC) in spherical symmetric spacetimes, LEC in Axially Symmetric Spacetimes, Silhouettes, Frequency shift and Light beam focusing.

The next section **Raytracing and Transfer function methods** is devoted to taking into account the influence of curved spacetimes on photons passing through them is the crucialin gredient of modelling astrophysical phenomena. If radiation originates in the relativistic systems then influence of the spacetime on generation and transport of radiation must be considered. The discussion is focused on transport of radiation. The two techniques are used: 1. Raytracing method based on integration of null geodesics parametrized by an affine parameter s usually normalized such that at initial point s = 0 and s = 1 at final point. This method is suited to model problems involving interaction of matter and radiation. Typical example of use of raytracing is radiating toroidal structure formed in the vicinity of a compact object. The emitted light beam, for particular values of impact parameters, is forced to reenter the torus body, where it interacts with the torus material (absorption, reemission, scattering). 2. Transfer function method when there is no need to carry out the interaction between matter and radiation. This method is faster then raytracing and is used in case of Keplerian disc imaging and associated astrophysical phenomena (light curves and spectral line profiles). The section consists of the following subsections as Extended objects images, Keplerian disk image, Toroidal images and CMBR (cosmic microwave background radiation) sky.

The next section **Astrophysical observations** discusses the observation of the black holes. The gravitational lensing and frequency shift phenomena of radiation coming from the radiating background (distant stars, galaxies), from their companion, or their accretion disk are useful for probe black holes. The radiation sources containing a black hole (or superspinar, naked singularity) provide the output radiation spectra, intensity, intrinsic luminosity, polarisation. The curved spacetime modifies those initial output properties and leaves its ”fingerprints” in the pattern of observed radiation. If one assumes steady thin disk model, the thermal radiation originating from the friction between two adjacent layers forms spectral continuum parameterised by averaged temperature of the disk surface.

The observations show that pure spectral continuum is strongly modified. The AGN (Active galactic nuclei) sources contain in their spectra resolvable iron emission lines. One of the propositions of their origin expects that they come from fluorescence by X-ray irradiated gas. In reality, the environment in the disk is wild and far from steady regime. The strong magnetic field and turbulences in plasma give rise to hot spots in the smooth face of the disk. The hot spots are regions hotter then the averaged surrounded gas, and their light curves modify the pure spectral continuum. The spacetime geometry strongly modifies the shape and the width of the original spectral lines and forms characteristic shape of the light curves from the hot spots, as the photons coming from the source to us must overcome the strong gravity regime in the vicinity of the black holes and superspinars (at r < 20M say) where effects of frequency shift and focusing play crucial role.

In this section the author describes in detail two phenomena: the profiled spectral line of radiation from Keplerian disk, and light curve whose radiation originates in the hot-spot on circular orbit around a black hole, giving the typical fingerprints left by particular theory of gravity. The section consist of the subsections as Keplerian disk, Profiled spectral lines and Light curve of a hot spot.

The last section **New directions of research** summarizes the future prospects on Motion in regular spacetimes, Motion along null geodesics of the spacetime metric and its electrodynamically modified variant as Circular geodesics and Estimates of time delay for hyperbolic orbits and finally the recently discovered Gravitational waves.

The habilitation dissertation of Dr Jan Schee is mainly devoted to optical phenomena connected to astrophysical processes arising around black holes and naked singularities governed by general relativity and some of the recently discussed alternate gravity theories, or candidates of quantum gravity theory. The following main results have been obtained in the dissertation: A variety of relevant optical effects has been treated: construction of various black hole shadows, gravitational lensing of light by gravitational compact objects, optical appearance of accretion discs around black holes, profiled spectral lines of accretion Keplerian discs or accretion tori around gravitational compact objects.

The habilitation dissertation 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 12 of them which are 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, alternate theories of gravity 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 results of 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 few number of stylistic errors and typos. For example, in page 27: (see Fig ?? bottom), in page 28: see Fig. ?? top, in page 38: the Carter equations (??) etc. Formula for relativistic factor for representative astrophysical bodies should have opposite ratio but the values in the table 1 are correct. In general, they can not affect the assessment of the high scientific value of the results presented.

The scientific and practical significance of the work is determined by the ability of the developed formalism in the dissertation to analyze the optical 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. In addition, analysis of their silhouettes makes it possible to design new tests to verify the general relativity and other alternative theories of gravity. Moreover, the results of research can be used to obtain estimates of different parameters of black holes such as rotation and other parameters, as well as the parameters that appears due to the higher-order corrections in the alternate theories of gravity. 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 alternate gravitational objects as superspinar etc. Thus, the habilitation dissertation is performed at a high scientific level and the results can be described as a big scientific achievement.

The habilitation dissertation ‘Optical phenomena probing the gravitational field of compact objects governed by alternative theories of gravity’ meets all the requirements of the regulations on the procedure for the award of scientific titles in the Czech Republic and may be admitted to the defense at the Silesian University in Opava and the author, Dr Jan Schee certainly deserves the award of the scientific title of Docent (Associate Professor).

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