To the Scientific Council of the Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences

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Statement on the PhD thesis by David Anthony Abarca

MSc David Abarca has submitted a thesis entitled "Numerical simulations of accretion onto neutron stars". The thesis contains the introductory part and three papers:

Paper I. Radial oscillations of a radiation-supported levitating shell in Eddington luminosity neutron stars, by **David Abarca** and Włodek Kluźniak (2016), MNRAS, 461, 3233-3238

Paper II. Radiative GRMHD simulations of accretion and outflow in non-magnetized neutron stars and ultraluminous X-ray sources, by **David Abarca,** Włodek Kluźniak and Aleksander Sadowski (2018), MNRAS, 479, 3936-3951

Paper III. Beamed Emission from a Neutron-star ULX in a GRRMHD Simulation, by **David Abarca**, Kyle Parfrey, and Włodek Kluźniak (2021) ApJ Letters, 917, L31 (7pp)

The doctoral thesis is devoted to the numerical study of the accretion process to the neutron stars. A unifying theme of the presented research is super-Eddington luminosity, when radiation produced in the vicinity of a compact object is important for the dynamics of accretion. Part of the work was analytical, while another part was done using simulations with the general relativistic radiation magnetohydrodynamics codes.

In section 1.1 of the introductory part, the author starts with an extensive review and basic formulae for the general relativistic radiation magnetohydrodynamics. The details of the numerical methods are discussed in section 1.2. The author goes into details of the Godunov type methods, higher-order methods, solution of stiff ordinary differential equations, how to deal with zero-divergence magnetic field, problems of high magnetization, and description of the Koral code. In Section 1.3, the basics of accretion disk theory is reviewed. This includes thin disk, MRI, ADAFs, as well as accretion at super-Eddington rates. This section is clearly missing some relevant references. Section 1.4 is devoted to accretion onto neutron stars, ultra-luminous X-ray sources (ULXs) and ULX pulsars, the theme of the thesis. In Section 1.5, a setup of the simulations is described in great details. A summary of the thesis and the refereed articles is given in Section 1.6. In the end, there is a bibliography of more than 100 papers. The introductory part is followed by the three papers.

Paper I is devoted to studying dynamics of a gas surrounding a neutron star that emit radiation close to the Eddington limit. The idea is that the gas can oscillate around some equilibrium position. This oscillation may be related to the phenomenon known as kilohertz quasi-periodic oscillations observed from accreting neutron stars in low-mass X-ray binaries. The author has computed the frequency of oscillation of the incompressible radial mode for a geometrically and optically thin layer and showed that this mode is overdamped by radiation drag. The paper contains detailed analytical model for the phenomenon as well as numerical calculations confirming analytical results.

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In Paper II, the author performs 2D general relativistic radiation magnetohydrodynamic (GRRMHD) simulations of the accretion disks which accrete onto non-magnetized neutron star at super-Eddington rates. Another simulation is made for the black hole instead of the neutron star. The black hole simulations show a strong outflow develops that collimates the accretion disk emission into a narrow cone. The radiation becomes beamed and the apparent luminosity within the cone becomes strongly super-Eddington. Such a model can be applied to some ULXs. The neutron star simulations produce a wind too but more spherically symmetric and producing about 1 Eddington luminosity. The author has concluded that such a setup is not likely is relevant for explaining ULXs, in particular, to recently discovered ULX pulsars, because pulsations will be likely washed out by scattering in the optically thick outflow (if they can be produced in the first place by a non-magnetic neutron star). Simulations have been done with the code koral developed by Aleksander Sadowski.

In Papers III the author proceeds with GRRMHD simulations of super-Eddington accretion, but now onto a magnetized neutron star. The author modified koral code to deal with high magnetization in the neutron star magnetosphere. The author considers rather low field star and rather high accretion rate, so that the spherization radius is much larger than the magnetospheric radius. This results in a strong outflow that can collimate radiation produced by the central source. The end result is that the apparent luminosity may be strongly super-Eddington if viewed along the symmetry axis. The author has concluded that accreting neutron star with a relatively weak field can emit beamed emission and can be a good candidate for a ULX.

The work presented in the thesis is published in three refereed papers in high-profile journals. Abarca is the leading author in all three of the papers and has carried the main responsibility for their writing. The amount of work put into all these papers by the author is substantial and the research has been performed according to high scientific standards using proper methods. The thesis constitutes a coherent collection of research papers on a similar topic. The language of the thesis is clear. The total input can be considered as fully satisfactory for the PhD thesis. In my view, the thesis is very good, but a little short of being awarded "with distinction".

Summing up, I consider the doctoral thesis of David Abarca to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Yours sincerely,

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