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Review of the PhD Thesis by Fatemeh Kayanikhoo,
fn "Numerical simulations of accretion onto neutron stars".

PhD Thesis of Fatemeh Kayanikho deals with numerical simulations of super-Eddington accretion onto the neutron star with a dipolar magnetic field of moderate strengths (1010−11 G). The goal was to find the magnetic dipole strength and accretion rate at which the accreting neutron star exhibits the apparent luminosity of observed ULXs. The whole presented research relies on general relativistic radiative (GMRRMD) numerical simulations performed with the Koral code.

The thesis includes one paper already published and one ready for publication at the moment of the Thesis submission. Chapter 2 includes a refereed article (Paper I) on „Energy distribution and substructure formation in astrophysical MHD simulations" by Kayanikhoo and coauthors, published in MNRAS 527, 10151-10167. Chapter 3 describes an original work on the „Study of Super-Eddington accretion onto neutron stars with moderate magnetic field". Chapter 4 describes part of the work devoted to the impact of magnetic dipole strength on outflows and beamed emission in the form of a stand-alone article (Paper II) prepared for publication in Astrophysical Journal Letter. Chapter 5 summarizes the results of the PhD project.

In Chapter I the author introduces the astrophysical context of the PhD research project. The main part of Chapter I introduces the topic of ultra-luminous X-ray sources (ULX) driven by super-Edington accretion, X-ray binaries, magnetohydrodynamic processes, mechanisms of super-Edington accretion, radiative processes, and the mechanism of pulsating ULXs. The remaining part of Chapter I introduces equations of general relativistic radiative magnetohydrodynamics and outlines the corresponding numerical simulation techniques. The presented brief review includes a summary of previous work with particular attention put to the work of Dr Aleksander Sądowski, the author of KORAL code Dr David Abarca, a former PhD student of Prof. Włodzimierz Kluźniak working on a related topic with the same simulation code.

Chapter 2. is devoted to the testing of magnetohydrodynamic algorithms of two numerical codes, PLUTO and KORAL by quantifying and discussing the impact of dimensionality, resolution, and code accuracy on magnetic energy dissipation, reconnection rate, and substructure formation. The performer tests aim to validate the KORAL code as an appropriate tool for the undertaken studies planned within the PhD project of Mrs Kayanikhoo discussed in subsequent chapters. The tests rely on a quantitative comparison of results obtained with relativistic and non-relativistic, resistive and non-resistive, two- and three-dimensional set-ups of the standard Orszag–Tang MHD test problem. The tests demonstrate that the results of both the codes are consistent, although reveal minor differences, resulting from different implementations of numerical MHD solvers.

Results presented in this chapter do not directly refer to the astrophysical context of the Thesis, nevertheless, the chapter presents an important part of the overall research project, since validation of complicated simulation codes, by comparison of standard test results to the analytical solutions or results obtained with other simulation codes, is crucial in the field of computational astrophysics.

In Chapter III the author presents numerical simulations of super-Eddington accretion onto the neutron star with a dipolar magnetic field of moderate strengths (1010-11 G) using the Koral code. The goal was to find the magnetic dipole strength and accretion rate at which the accreting neutron star exhibits the apparent luminosity of observed ULXs. The simulations have been performed with six different dipole strengths and mass accretion rates. Simulation results demonstrate that the weaker dipole results in higher apparent luminosity compared to the stronger dipole. In weak dipole simulations (1010 G), the apparent luminosity is about 120 Eddington units, while for the dipole of (1011 G), this value is only 40 Eddington units.

This chapter is well written. Its scientific contents, although not yet published, document high-level research, based on sophisticated and technically difficult numerical experiments. These research results make an important contribution to the current research on ULX sources.

In Chapter 4, the author presents a paper intended for submission to the Astrophysical Journal Letters (ApJL). This letter focuses on the beamed emission from super-Eddington accretion onto a neutron star with a magnetic field strength 1010- 1011 G with the accretion rate exceeding 200 Eddington luminosities. The presented simulations reveal that, despite the lower accretion rate in the case of the weak dipole field (1010 G), the apparent luminosity is higher than in the simulations with stronger fields. Accretion is found to power strong outflows which collimate the emergent radiation of the accretion columns. The apparent luminosity exceeds 100 Eddington units, consistent with the luminosity of detected ULXs. The author finds a surprising result: the collimation cone widens with increasing magnetic field and the apparent luminosity of the neutron star is substantially larger for weaker magnetic fields (1010 G) than for the stronger ones (1011 G).

Chapter 4 demonstrates the intriguing properties of a magnetized neutron star. In my opinion, the novelty and high quality of the research indicate that these results will be accepted for publication in a reputable astrophysical journal.
Finally, Chapter 5 summarizes the Thesis results and provides additional discussion on the challenges of the project and future plans that include 3D simulations of super-Edington accreting neutron star with an inclined magnetic axis. The candidate obtained an NCN grant for this project.

Despite my generally positive impression of the dissertation as a whole, I do have some criticisms of the understanding and presentation of basic magnetohydrodynamical processes in Paper I.

The list of key elements of the numerical algorithm used in code Koral is presented rather chaotically. Numerous terms specific to computational fluid dynamics appear without definitions or even hints of their meaning. The list is readable for experts of computational astrophysics, but not necessarily for other experts of the main dissertation topic. Here are some examples: „primitive and conserved quantities", „CFL condition", „Riemann problem", „HLL Riemann solver", „cell-centered primitives", and „Flux-constrained transport". This way of presenting the computational tools used in the paper does not help the reviewer assess whether the candidate understands the research methods used. Despite these complaints addressed to the description of numerical methods, the presentation style of the dominating parts of the introduction section, presenting astrophysical context, is clear, concise, and is logically structured.

I also have some comments on the published Paper I:

Eq. 10 – magnetic diffusivity is not identical, but proportional to. Resistivity - compare physical units.

p.10154, Sect 4.1, first paragraph: „... in grid-based codes, the flux is computed over the surface of every grid cell. In such a calculation, there is some amount of computational dissipation, so-called numerical resistivity." Numerical dissipation of magnetic field is an immanent feature of numerical integration schemes, originating from the finite element differencing replacing true derivatives, and depends rather marginally on the choice of cell face centering of magnetic field components.

p.10155+: Why density slices are chosen to demonstrate ongoing reconnection. The resistive dissipation rate (\eta j^2) can be used as a direct and better indicator of magnetic energy dissipation.

P 10163: . Concerning the statement „We showed that in Ideal- MHD and Res-MHD simulations magnetic energy converts into internal energy and heats up the plasma.": It should be noted that the „ideal MHD approximation" neglects all dissipation effects.

The magnetic field dissipation in ideal MHD results from inaccuracies of numerical algorithms. The phrase „magnetic dissipation in Ideal MHD simulations" sounds inconsistent. The author should know that ideal MHD simulations are in fact resistive simulations with resistivity related to the numerical diffusivity of the algorithm.

Despite these, rather minor, I am fully convinced that the results of the original research by Fatemeh Kayanikhoo, presented in the dissertation, represent an original solution to a scientific problem of magnetized accretion onto neutron stars and an explanation of important aspects of ultraluminous X-ray sources. The dissertation demonstrates the candidate's general theoretical knowledge and ability to conduct independent research in the discipline of astronomy.

To my opinion the Doctoral Thesis of Fatemeh Kayanikhoo meets the requirements of Article 187 of the Law on Higher Education and Science of 20th July 2018. Therefore, I request that this dissertation be admitted to a public defense.