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*To: Prof. Adam Sawicki*
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***Referee's report on Ph.D. Thesis presented by Ishika Palit***

Dear prof. Sawicki,

In order to fulfill the requirements for the degree of Doctor of Philosophy (Ph.D.) in Physics at the Center for Theoretical Physics of the Polish Academy of Sciences in Warsaw, Ms. Ishika Palit has prepared the Thesis titled "Selected aspects of low angular momentum accretion onto a black hole". The Thesis was prepared under the supervision by prof. Agnieszka Janiuk and submitted for defense in summer 2021. The Thesis presents the original research conducted by the candidate and described in seven sections (100 pages) including two published first-author papers in respected professional journals. The volume includes an explanatory summary and an overview of main aspects of the adopted research line, as well as the list of relevant references in the literature and additional author's publications in conference proceedings.

Following an introductory overview on astrophysical black holes and the basic properties of transonic accretion in Sec. 1, the author describes the numerical code HARM (definition of the coordinates, set-up of the grid, parallelization) that has been employed and adapted for her investigation (Sec. 2). Then, specific properties of the so-called Low Angular momentum accretion Flows (LAF) are introduced. These first three section provide an elementary framework for the principal results of the author's original work, which are described in two papers by Palit et al. (2019, 2020) published in Monthly Notices of the RAS and The Astrophysical Journal. The three introductory chapters read well and they provide a broader context, references to the literature and description of code tests beyond to what is included in the specialized papers. Both stellar mass systems, namely, black holes in X-ray binaries (XRB), and supermassive objects in nuclei of active galaxies (AGN) are discussed. I believe that the text is mathematically correct (although see some minor points listed below). However, in order to obtain a complete picture, one needs to examine also the introductory sections in both mentioned papers and combine different pieces of information in order to complete the whole picture.

Chapters 4 and 5 of the Thesis consist of reprints of two articles: Paper I: “Effects of adiabatic index on the sonic surface and time variability of low angular momentum accretion flows”, by Ishika Palit, Agnieszka Janiuk, & Petra Suková, MNRAS 487, 755-768 (2019); and Paper II: “Clumpy wind accretion in Cygnus X-1”, by Ishika Palit, Agnieszka Janiuk, & Bozena Czerny, ApJ 904:21 (2020). As mentioned above, the adopted approach is focused on the method of numerical simulations, which is among the main experience developed in the Working Group in the Center for Theoretical Physics, where this work has been completed. I read both papers with great interest.

Paper I deals with one of defining properties of accretion flows onto black holes, namely, the transition of the gas inflow across the sonic point near above the event horizon, where the pull of gravity is overwhelmning and the material has to proceed in the inward direction in the absence of any hard surface in the centre, described here by Kerr metric. The author concentrates of the inflows that start as sub-Keplerian at large distance. This important situation has been previously examined by numerous authors (seminal works are cited and the principal results are explained in the Thesis). The author rightly points out the fact that thermodynamical properties of the gas are equally important for the flow behaviour as the structure of the black hole gravitational field. Therefore, this work presents a novel study of the impact of different adiabatic index gamma on the formation of shocks and sonic surfaces within the inflow. It is shown how the value ranging from gamma = 4/3 to gamma = 5/3 is reflected in the shock oscillatory behaviour and, consequently, the accretion rate variations and the emerging Power Density Spectra of obervaed radiation signal.

Paper II examines the dynamical behaviour of the transonic, low-angular momentum inflow and the resulting stochastic fluctuations in the particular source of high-mass X-ray binary Cygnus X-1. This is the enigmatic prototype of wind-fed black hole and one of the brightest X-ray sources in the sky. By parallelizing the code, the author can study the variability features on short time scale below 100 sec. The development of gaseous clumps at the outer boundary of inflow have not yet been properly understood and the Paper contribudes this research line. With interesting information about the expected Mach number, density, and the angular momentum distribution.

Chapt. 6 of the Thesis presents an outlook to future research plans for follow-up investigations that the author has partly started. I see that the projects on including the effects of self-gravity and non-axisymmetric perturbations of the accretion flow are very relvan and ambitious, nevertheless, they certainly reach beyond the scope of the current Thesis content. Finally, Chapter 7 presents a summary of the main results of the Thesis.

I have not noticed errors in the scientific arguments and derivations. The language of Thesis is cultivated and I can find only a small number of language errors, typos and misprints. Nonetheless, I may suggest a few questions for further clarification during the discussion. For example, the introductory sentence (p. 1) states that “Black holes are the points in space where gravity is strong…”. Even if it is understandable what the author intends to describe regarding the strong gravity effects near black holes, it would be more precise if the classical space-time picture is maintained. Further down that page, the sentence “Structural details of a black hole…” is difficult to understand. The statement “Out of four known exact solutions to Einstein’s field equation, one of them gives…” (p. 2) is unclear; obviously there are many more exact solutions described in the literature. When discussing zero electric charge of astrophysical black holes (p. 4), it would be useful to mention the possibility of non-vanishing Wald’s charge in the presence of an external magnetic field. Because the HARM code employs General Relativity, I am not sure if there is any substantiation to introduce pseudo-Newtonian potential (p. 8); it is not a fully consistent theory and apparently it is not needed in this work, so it can only create confusion to the reader. On the bottom of p. 15, “Bondi accretion describes…” is probably mistaken for Bondi-Hoyle-Lyttleton model. The two published papers have passed a thorough referee process as well as the language editing, and so here I do not find any mistakes in the main Chapters 4–5.

To a more detailed discussion I would like to suggest the statement “Due to an abrupt drop in radial velocity and kinetic energy, the temperature in this region tends to be very high” (p. 86); is this conclusion a generic feature of the discussed solution? Further down, the author points out that “It is not possible to explain black hole accretion using a fixed Equation of State (EoS) from infinity to the horizon”; however, I understand that the whole work employs the polytropes with just a limited chage of its gamma index, so the statement could be elaborated in more detail.

A very minor quibble concerns the mass of Cyg X-1 black hole; while the author adopts a canonical value of 20 solar masses, older estimates used to be lower than that and the more recent accurate measurements, vice versa, seem to point towards 21. I assume that this does not change much on the quantitative results of the Paper II. However, it may be interesting if the Candidate mentions during the Thesis discussion the main origin of uncertainties of the black hole mass estimates in Cyg X-1. Also, what the simulations predict for the future phase of the system when the donor star eventually fills the Roche lobe?

Let me clarify that the above-mentioned questions are meant to initiate discussion of the research and the interesting results presented in this Thesis. I consider the presented work to be satisfactory.

**I conclude that the presented dissertation meets the requirements expected for Ph.D. theses and the Candidate has clearly demonstrated her qualifications and original ideas in astrophysics. Therefore, I recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense.**

Yours sincerely,

prof.RNDr. Vladimír Karas, DrSc.

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