Doctoral Thesis Referee Report

Title: Computer modelling of accretion processes in binary systems with black holes and neutron stars

Author: Debora Lančová

I have been asked to review a doctoral thesis that has been submitted at the Institute of Physics of the Silesian University in Opava by Debora Lančová.

The objective of the thesis has been to focus on the problem of black hole accretion disks and other relativistic compact objects from the perspective of advanced numerical simulations and of modeling their spectral and timing properties in X-ray domain.

General assessment of the thesis

The thesis has been written as an annotated collection of 4 refereed and 2 non-refereed papers, where in three papers Ms. Lančová is a leading author (first or second) and in other three papers is a contributing author (a member of the team).

The first two chapters contain some general introduction to accretion onto compact objects (black holes and neutron stars) and to the physics of accretion disks. Despite their relative brevity, they contain everything that is needed for an introduction. It is worth pointing out several original and stylish illustrations of the accretion systems and processes that accompany these chapters.

Then comes the third chapter about GRMHD simulations of sub-Eddington accretion disks with a special focus on KORAL, which represents one of the most advanced and sophisticated code on the market of radiative GR-MHD simulations. This chapter makes an excellent summary and one of the best descriptions I have seen of the equations and numerical procedures that are involved in implementations of GR-MHD codes. After some expansion, this chapter could become a beautiful description of the physics that is behind KORAL and stand as a part of its manual.

The fourth chapter gives a summary of the puffy disks that have emerged from performing numerical simulations of sub-Eddington accretion disks as a solution that mixes properties of both thin, slim and thick analytical models of accretion disks. This part describes the initial setup of KORAL code, and physical and observational properties of the resulting puffy disks.

The final fifth chapter is dedicated to modeling the HFQPOs and their application in extracting information about the geometry and properties of the central object in neutron-star and black-hole these sources. It explores the light-curve modulation in scenarios involving either an oscillating torus or a torus plus a luminous boundary layer.

During her post-graduate studies, Ms. Lančová has made a number of influential contributions to astrophysics. The most important of all has been the introduction of puffy disks - a novel type of accretion disk based purely on the results of numerical simulations. Her two referred papers on the subject have already accumulated some 40 citations proving their impact and importance. Moreover, her results provide invaluable insight and help theorists to explore the thin/slim disk transition. They are at the same time useful in testing the predictions of simplified analytical models and verifying their validity and ability to model the observed spectral data.

I conclude that the aims of the doctoral thesis have been successfully reached, some problems have been solved and the thesis raises many new interesting and challenging questions that ought to be answered. The thesis has been written very carefully, in very good English with only a few imperfections and typos. The work has proved the ability of the candidate to perform qualified independent and high-level research and to present her results in the renowned journals and in a clear and comprehensive way.

Specific comments and remarks on the thesis text

Section 1.3.1. describes the various spectral states of black hole microquasars. There is, however, a special spectral state that appears on the transition between hard and soft intermediate states. This so-called steep power-law state (SPL) is characterized by a relatively weak thermal component and dominant non-thermal component with a quite steep photon index. This spectral state is particularly important from the QPO perspective because the high-frequency QPOs in black-hole microquasars tend to almost exclusively appear in it.

In Section 2.1 that explains the concept of Eddington luminosity (for spherical accretion), the introduction of the rest mass-to-energy conversion efficiency factor deserves few more comments as there is an implicit topology transition from spherical to disk accretion. The same holds for the claim that Eddington luminosity is also valid for disk accretion, which is contradicted by the following sentence that permits super-Eddington disks.

In Equation 2.10, the summation shall go only to N-1.

In Section 2.3.2., it is the contravariant component of the metric tensor that determines the location of the inner and outer event horizon (g^rr=0, instead of g_rr=0).

In Figure 2.6., the hottest parts of the disk contribute with the hardest spectrum. The inset plot showing the spectrum has reversed color notation.

In Section 4.4., it would be nice if Fig. 9 from Paper 2 was copied there illustrating the discussion of the observational properties of puffy disks.

Questions and suggestions for discussion

The puffy disk spectra have a shape that is significantly different from the multi-color black-body (MCBB) spectrum of the thin disk. Still, the observed BHXRB spectra seem to be rather similar in shape to MCBB spectrum even at mass accretions rates that are around 0.5 L_Edd, i.e. to those that have been simulated with puffy disks. On the other hand, the observed spectra tend to become much softer than what the thin disk MCBB model predicts as the mass accretion rate increases. Therefore, the real spectra (in mid sub-Eddington regime) does look neither like the thin disk model spectra, nor like puffy disk spectra. In this respect, does the puffy disk seem to provide a qualitatively better description of reality than the analytical models?

Although puffy disks combine properties of thin, slim and thick analytical models, they are close to slim disks. In the current slim disks, one of the inconsistencies is the vertical equilibrium treatment that underestimates the scale height of the disk. If a slim disk was taken with H/R=1, how different would its observational appearance be compared to puffy disks?

The observational appearance of a puffy disk is computed a-posteriori using a post-processing code. A good fraction of thermal photons is comptonized in the funnel region. The comptonization in effect leads to a quite rapid cooling of the electrons that have to be re-energized. Is there an account of how much energy is taken from the electrons and how it would affect the result if this additional cooling was included in the simulation itself (which I understand is not)?

With finally now entering the age of X-ray polarimetry, it would be interesting to know the polarization properties of the outgoing radiation. Is HEROIC capable of X-ray polarization or are there plans to include it?

Final recommendation

After a detailed study of the thesis, I evaluate its scientific level as high, the work fully meets the expectations and standards that are required, results of the performed research have already been published in high-impact international journals. The thesis presents new scientific achievements and the candidate has proved her creative abilities in the field of astrophysical research.

Therefore I recommend to accept the submitted thesis and propose to award Debora Lančová the academic degree Philosophiae Doctor (Ph.D.).

Praha, September 17, 2023

Mgr. Michal Bursa, Ph.D.

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