Centrum Fizyki Teoretycznej
Polskiej Akademii Nauk
02-668 Warszawa, Al. Lotników 32/46
REGON 000844815
tel: (+48 22) 847 09 20, tel/fax: (+48 22) 843 13 69
email: cft@cft.edu.pl
www.cft.edu.pl

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Report on the Doctoral Thesis of Mr Varadarajan Parthasarathy,
entitled
"MHD simulations of time varying astrophysical flows"

prepared in the Nicolaus Copernicus Astronomical Center,
Polish Academy of Sciences

The topic of this doctoral thesis deals with numerical modeling of processes that act in matter in the close vicinity of accreting stellar-mass black holes and neutron stars. These compact objects are observed in the nearby Universe in ubiquitous systems, commonly named as the X-ray binaries. Measurements provided by a number of space missions are giving the information about the timing properties of the accretion flows in such systems. In particular, the quasi-periodic oscillations of high frequencies, can be attributed to the resonances produced in the innermost parts of the flow, located very close to the black hole horizon. In the case of accreting neutron stars, the timing properties may reveal the change of rotation period of the star, which results in a phenomenon called a millisecond pulsar.

The methodology used by Mr. Parthasarathy in his thesis is based on advanced numerical techniques and algorithms. His computations are performed using the code PLUTO, which was originally developed by the Italian group of prof. A. Mignone, and made publicly available together with its source files and some documentation. The software provides solver for hydrodynamic equations in Newtonian gravity, and is now widely used in the astrophysical community in various contexts. Here, the code was supplemented with the pseudo-Newtonian potential originally proposed by Kluzniak and Lee (2002), which describes the motion of matter in the strong gravitational field with a good accuracy. The Author also uses specific setups for the initial conditions, to model the oscillating tori around black holes, as well as around magnetized neutron stars. The millisecond pulsar simulations consider also rotation of the neutron star and specific boundary conditions that allow for an interaction between the disk and stellar magnetosphere, as well as for the stellar wind outflows.

In addition, the Author of this thesis presents his own contribution to the numerical scheme, but implemented to a different code. He worked on the Riemann solver and introduced it to the hydrodynamical code PIERNIK, which was originally written by the Polish group led by prof. Hanasz. In his thesis, Mr. Parthasarathy presents the overall description of the Riemann problem, and the discussion is supplemented by the suite of numerical tests. These are considered standard in numerical astrophysics, and prove that the code performance is satisfactorily accurate.

The Thesis of Mr. Parthasarathy consists of 5 Chapters.

Chapter 1 contains a very brief introduction to the topic of accretion flows (2 pages) and a few paragraphs describing the content of the thesis. The Author highlights the advantages of the present approach, i.e. the 'numerical experiment', over the earlier, analytical works, and stresses the fact that his simulations of the oscillating tori are the first of this kind.

In Chapter 2 the Author presents his simulations of the oscillatory behaviour of a torus accreting onto a Schwarzschild black hole. The initail condition is that of an equilibrium torus (Hawley 2000). The simulation adopts pseudo-Newtonian potential and polytropic equation of state, and a grid of models is studied, for a range of values for the inner radius of the torus. Three different types of velocity fields that perturb the initial equilibrium configurations, are imposed. As a result of the simulation, the frequencies and modes of oscillations are found and expressed in the units of Keplerian frequency at the inner radius.

Chapter 3 presents the study of a similar oscillating torus, but now it accretes onto a neutron star. In this case, only one set of parameters defining the torus geometry is used, and the models differ with respect to the star's magnetic field strength, and with the type of velocity perturbations.

Chapter 4 contains the most interesting study, which is the accreting milisecond pulsar's evolution. The pulsar is modeled with a rotating neutron star of a given mass and radius, and embedded in a dipolar magnetosphere. The star is surrounded by a thin disk, with density and pressure profiles taken from Zanni and Ferreira (2009), and the angular momentum transport is supplied by both kinematic and magnetic viscosity. The simulations show how the accretion cloumn forms along the polar axis and the matter starts reaching neutron star's surface. Also, some matter is taken away from the domain by the wind.

Chapter 5 presents the Riemann solver implemented by the Author to the PIERNIK code, which is based on the Harten-Lax-van Leer (HLL) approximation. The chapter contains an extensive description of the code itself, and the numerical scheme construction is presented in a very pedagogical manner. This chapter does not present any original simulations with PIERNIK code, such as the pulsar's model presented in the previous chapter, however it would be interesting to see them as a result of some future work.

My comments and questions on the content of the thesis are as follows.

1) The Introduction chapter seems to be quite short. Not all the concepts are defined (e.g., the 'boundary layer', or 'QPOs') and in fact this chapter will be understood only by the specialists in the field. I would expect the traditional dissertation to contain a bit more elaborate and general Introduction to the topic of accreting compact stars in binary systems, which itself is very broad.

2) There is no chapter, which in fact would aim to summarize the assumptions and results of this whole research in the context of the observed phenomena related to the real sources. Several examples of specific objects, with discussion

that would compare the observed QPO frequencies with the simulations results, or the magnetic fields measured in the millisecond pulsars with these adopted in the initial conditions for the PLUTO code, could make this thesis really beautiful and outstanding.

3) In Chapter 2, the Author should give some discussion of the last model, T3, with the distance between the radius of pressure maximum and inner radius of the torus, rt=0.36, which is twice as much as for the other models. Why only vertical velocity perturbation is studied in this case? Are there numerical or other reasons?

4) Why in the case of oscillating torus around a neutron star the timing analysis is based on the mass accretion rate onto the star's surface, while in the former simulations, i.e., the accreting black hole, the probed quantity was the total density of the torus, given by Eq. 2.9? In other words, was the mass not accreting onto the black hole in the simulations presented in Chapter 2?

5) Some of the models presented in Chapter 3 include magnetic field, i.e. the dipole field of the neutron star. However, the equations of magnetohydrodynamics are presented only in Chapter 4. Is the field evolving also in the simulations presented in Chapter 3?

6) What is actually the X-ray source presented in Figure 3.4? What is the definition of the 'quality factor'? Is it related to the instrument's time resolution?

7) In the millisecond pulsar simulation, the wind mass loss rate is measured from the pole down to the last open magnetic field line angle. Is it possible also to produce a wind loss at latitudes closer to the equator, i.e. from the accretion disk surface?

8) The initial rotation period of the neutron star is 5 ms. Due to the magnetic spin-up torque, and negative spin-down torque due to the wind loss (as I understand, this term means effectively spin-up), the spin of the star should increase. Is this effect accounted for during the dynamical simulation? If so, what is the final rotation period of the star, at the end of the simulation?

9) The Author claims to have modified the HLLD Riemann solver in the PLUTO code. Is this done with the same method as for the PIERNIK code? Have the

standard tests been performed on the PLUTO code with this new solver, similarly to the ones shown in detail in Chapter 5?

10) There are many spelling mistakes, mainly related to the confusion between the singular and plural forms of verbs.

Regardless of the above critical comments, I generally conclude that the thesis results are valuable and important for our understanding of tori around astrophysical black holes and for accreting neutron stars. It also proves the Author's ability for pursuing original scientific research.
Therefore I conclude, that the presented dissertation meets the usual and formal requirements made to the PhD theses. Hence, I am requesting the admission of Mr Varadarajan Parthasarathy to the subsequent stages of the procedure, including the public defense.

dr hab. Agnieszka Janiuk
associate professor at the
Center for Theoretical Physics
Polish Academy of Sciences
Warsaw
Poland