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Subject: Review of the Ph.D. thesis of M.Sc. Vadym Khomenko

The dissertation submitted by Vadym Khomenko and titled "Superfluid Neutron Star Dynamics" is a collection of four articles supplemented with the Introduction chapter and extensive bibliography consisting of 123 entries. The main subject of the articles is related to the modeling of neutron star dynamics by means of two-component superfluid hydrodynamics. The topic of the Ph.D. thesis belongs to the active area of research in astrophysics. In this context, the candidate investigates the impact of the mutual friction coupling on the dynamics of glitching neutron star. All the **articles can be regarded as series of thematically related papers**, and thus **they satisfy requirements associated with the form of the dissertation**.

The articles are **published in very good quality and peer-reviewed journals**: Monthly Notices of the Royal Astronomical Society (x2) (IF=4.957), Publications of the Astronomical Society Of Australia (IF=5.138), Physical Review D (IF=4.413). In two cases, V. Khomenko is listed as the first author, and in two other cases he is listed as the second author. It reflects his significant contribution to these works. Indeed, according to provided declarations, **the contribution of the candidate is either dominant** (90% and 75% for papers 1 and 3, respectively) **or significant** (40% and 45% for papers 2 and 4, respectively). At the time of writing this report, the papers received in total 39 citations (according to Web of Science). It indicates that the works of V. Khomenko **already attracted significant attention from the neutron star community**.

In papers 1-4 the candidate utilizes two-fluid hydrodynamics to describe the dynamics of glitching neutron stars. In this macroscopic description protons and electromagnetically locked with them electrons are treated as the first fluid, being in a normal state. Neutrons are treated as the second fluid, being in a superfluid state. The fluids are coupled via the so-called mutual fraction term, which encodes microphysics (internal excitations of the quantum system, interaction of quantum vortices with nuclear impurities, spatial arrangement of the vortices, etc.). Its form is still debatable, and the works of V. Khomenko contribute to a deeper understanding of its relation to astronomical observables: glitch sizes, rise and relaxation times, oscillation modes. In this context, the main findings are:

- paper 1 (PASA 35, 20, 2018): Vortex accumulation process at the edges of pinning regions (regions where the pinning force is relatively strong) introduces additional nonlinear terms to the mutual friction. Technically, these terms can be parametrized by an additional coefficient, namely a fraction of vortices that are not pinned. Besides standard exponential solutions of the glitch rise, they can lead to a new type of solutions with a

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linear scaling. Depending on the specific setups (different values of coefficients), they can induce different dynamics of the star. In particular, the new terms can give rise to glitch precursors or even cause anti-glitch (decrease of the angular velocity of the star).

- paper 2 (MNRAS 481, L146, 2018): Values of coefficients defining the mutual friction term (as discussed in paper 1) were constrained based on observations of glitches in Crab and Vela pulsars. It was found that the extracted mutual friction parameter B is significantly larger for glitches in Vela pulsar than in Crab pulsar. This finding points the candidate to the conclusion that glitches in the Crab pulsar originate from the crust. In contrast, an additional contribution from the outer core is expected in the case of Vela pulsar glitches. The work demonstrates how the glitch observables can be converted into information about the internal star dynamics.
- paper 3 (Phys. Rev. D 100, 123002, 2019): Solutions of two-fluid hydrodynamic equations were studied for standard (Hall-Vinen) and isotropic (Gorter-Mellink) forms of the mutual friction term. The first one is expected in the case of straight vortices and laminar flows, whereas the second one applies to turbulent flows where quantum vortices most likely develop a tangle. Special attention has been paid to investigating if hydrodynamical instabilities can emerge. The standard form of the mutual friction admits instabilities that develop rather fast in the form: Donnelly-Glaberson instability if there is imposed counterflow along vortex lines or two-stream instability if the counterflow is perpendicular to the vortex lines. Changing the form of the friction to Gorter-Mellink form stabilizes the system (instabilities are suppressed). It suggests that the following scenario may be relevant for neutron stars: once the glitch is triggered, instability develops that eventually leads to the appearance of turbulence in the interior. The turbulence acts as a stabilizer until it decays and the process can start again. Thus, the timescale for the decay of the turbulence may be related to the timescale to the next glitch.
- paper 4 (MNRAS 496, 5564, 2020): The paper tests the impact on observables, like glitch rise time and size distribution, of new nonlinear terms in the mutual friction emerging when the drag parameter R is allowed to be explicitly dependent on the velocity between superfluid vortices and the normal component. Physically, the new contribution to the mutual friction is associated with either Kelvin or phonon excitations. Since the correct functional form of the drag parameter is not fully known, various scenarios are considered: vortices are initially free or pinned, the system is accompanied by classical or quantum turbulence. As a result, the candidate identifies significant differences induced by these new terms compared to the standard case. Interestingly, the new terms explain the observed bimodal distribution of glitch sizes in the pulsar population within a single process, contrary to speculations that the bimodal distribution indicates multiple glitch mechanisms.

Clearly, works constituting the basis of Ph.D. **thesis of V. Khomenko provide a clear link between the mutual friction term**, which is determined by microphysics, **and astronomical observables**. Obviously, one can revert the process: by providing accurate data of glitch dynamics, it will be possible to pindown physical processes, and associated with them parameters, taking place deep in neutron stars. In my opinion, the results of papers 1-4 provide a solid foundation for future interpretation of new data sets.

The described series of papers is supplemented with a concise introduction chapter. It contains an overview of the general properties of neutron stars, including their structure, composition, and emission properties. A significant part of the introduction is devoted to the glitch phenomenon and superfluid properties of nuclear matter. From an editorial point of view, I find statements that need clarification, e.g.,

- page 9: *Neutrons in a Fermi sea interact through the long-range attractive interaction and form Cooper pairs like electrons do in conventional s-wave superconductors* (In general, neutrons interact via short-range nuclear force.)
- page 11: *Many pulsars exhibit a high degree of linear polarization, up to 100% in some cases.* (Not clear what type of polarization is discussed.)
- page 21: *A hydrodynamical model is applicable to length-scales bigger then inter-vortex spacing...* (Up to page 21, there was no discussion of the length scales associated with the problem, the mentioned scale it is introduced the first time in the next section.)

Also, some equations need clarification or additional comment, e.g.,

- eq. (1.2): Φ_0 is not defined.
- eq. (1.9): S is phase of the condensate wave-function.
- eq. (1.10): $\mathrm{curl}(v_s)=0$, only if there is no quantum vortices, otherwise $\mathrm{curl}(v_s)\sim\delta(r-r_v)$, where r_v is position of the vortex core.
- eq. (1.13): $v_s = k/2\pi r$ applies only to straight vortex; otherwise, one should use Biot–Savart expression.

From a general point of view, the introduction does not inform the reader much about how publications, being the basis of the thesis, are connected and how they contribute collectively to a better understanding of the glitch phenomenon. The author only briefly describes the main message of each paper separately in the last section of the introduction, with no summarizing statements of overall achievement. I find it as the weakest point of the introduction section. Also, in my opinion, a paragraph devoted to future prospects and challenges would improve the quality of the section. Here, I need to emphasize that these deficiencies do not significantly affect the very good overall assessment of the thesis.

In summary, **I assess that the submitted thesis by M.Sc. Vadym Khomenko fulfills the requirements for doctoral dissertations**. Publications that constitute its basis are of **high quality and significantly improve our understanding of the glitch phenomenon in neutron stars**. I request for **admission of the thesis to the public defense**. Moreover, due to very high scientific merit, I am asking for the distinction of the thesis.

Yours sincerely,

Wlazłowski

---- Gabriel Wlazłowski ----