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Assessment of the doctoral thesis presented by Ankan Sur

Ankan Sur presented a doctoral dissertation entitled `Magnetic fields in isolated neutron stars: from the interior to the exterior.' The thesis is 124 pages long. It consists of an introduction, a summary, and the following four research articles published either in Monthly Notices of the Royal Astronomical Society or in Publications of the Astronomical Society of Australia:

[1] AnkanSur, Brynmor Haskell, and Emily Kuhn, Magnetic field configurations in neutron stars from MHD simulations, *Monthly Notices of the Royal Astronomical Society* 459, 1360 (2020).

[2] Ankan Sur, William Cook, David Radice, Brynmor Haskell, and Sebastiano Bernuzzi, Long-term GRMHD simulations of magnetic field in isolated neutron stars, *Monthly Notices of the Royal Astronomical Society* 511, 3983 (2022).

[3] Ankan Sur, and Brynmor Haskell, The impact of superconductivity and the Hall effect in models of magnetised neutron stars, *Publications of the Astronomical Society of Australia* 38, e043 (2021).

[4] Ankan Sur, and Brynmor Haskell, Gravitational waves from mountains in newly born millisecond magnetars, *Monthly Notices of the Royal Astronomical Society* 502, 4680 (2021).

All these papers are devoted to a study of neutron stars and in particular to magnetic field configurations within neutron stars. The first two papers present results of numerical simulations of the evolution of magnetic fields.

Paper [1] describes a Newtonian magnetohydrodynamical (MHD) analysis. The star is assumed to be barotropic – the initial configuration is described by the Lane-Emden solution corresponding to the index $n = 1$ polytope. The gravitational potential is not evolved. An essential part of initial data is a specification of the initial magnetic field configuration. Initial configurations of the magnetic field investigated in this paper are either purely poloidal or contain a non-zero toroidal component. In both cases the system seems to settle to a quasi-equilibrium state, in which both poloidal and toroidal

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magnetic field components are present, and the energy contained in the poloidal magnetic field component exceeds the energy associated with the toroidal component. In the same study the authors attempted to investigate the development of turbulence, however the limited spatial resolution of the numerical grid did not allow for a clear conclusion about the obtained spectrum.

Paper [2] shows the results of a general-relativistic study. It is performed within the framework of general-relativistic magnetohydrodynamics, using the numerical code ATHENA++. In essence the idea of this investigation is similar to the previous Newtonian study [1]. Evolution is performed on a fixed background spacetime, corresponding to a static spherically symmetric Tolmann-Oppenheimer-Volkoff polytropic solution. Here again two different types of initial magnetic field configurations were investigated – a purely poloidal magnetic configuration and initial data containing both poloidal and toroidal magnetic field components. A purely poloidal initial configuration excites a toroidal magnetic field component, which decays during later evolution stages. Initial data containing a toroidal component of the magnetic field seem to lead to a more stable configuration. Similarly to the Newtonian analysis [1], the authors also performed a spectral analysis to search for turbulence-like behavior, but, as far as I understand, the obtained results do not allow to conclude about a Kolmogorov-type scaling.

I find both the Newtonian and general-relativistic studies to be interesting and well-done. In general, performing complex numerical simulations (even if one is not the author of the numerical code) requires a lot of tedious work in setting up and running the simulations and some maturity in post-processing and visualizing the results. Clearly Ankan Sur has proved to be capable of performing advanced magnetohydrodynamical simulations. The subject of both papers [1] and [2] is timely and important. The basic task in this line of research is to identify magnetic field configurations favored in the interiors of neutron stars.

My only critical remark to the presentation of the general-relativistic results of paper [2] is due to a lack of a clear general-relativistic description of the investigated model. For instance, we do not really know the coordinate system used in this study – what is the assumed gauge and the assumed time foliation of the spacetime? This could be important, as many of the quantities used in the presentation of the results depend for instance on the choice of the time foliation [this is the case of energies defined in Eq. (13)]. Also, since the equations solved by the numerical code are not listed in the paper, one must assume that the quantities used throughout this work have their usual meaning adopted in the majority of works in the field of numerical general-relativistic magnetohydrodynamics.

In the third paper, the authors search for stationary Newtonian configurations of the magnetic field within neutron stars. In this paper the authors present their own numerical code solving the appropriate Grad-Shafranov equation. The Grad-Shafranov is solved on a fixed, spherically symmetric fluid configuration (i.e., neglecting the back reaction of the magnetic field on the fluid). The authors applied their code to compute axially symmetric equilibrium configurations of the magnetic field, basing on the Hall approximation in the neutron star crust and the MHD approximation in the core. I have to say that I liked this study the most, as it shows an original contribution of the authors in terms of designing and testing their own numerical method.

Paper [4], published in the Monthly Notices of the Royal Astronomical Society, is devoted to a study of gravitational waves emitted by rapidly rotating pulsars. The authors investigate a rapidly rotating (newly born) pulsar under the influence of matter accreted along magnetic field lines and a neutrino driven wind of charged particles emitted from the star. Effective torques acting on the star and the corresponding spin evolution are considered. In this work equilibrium configurations of rotating stars are computed using a numerical code by Stergioulas and Friedman, which yields gravitational masses and moments of inertia. Finally, the amplitudes of the gravitational waves emitted by such a system are estimated. The character of this paper is dramatically different than the style of previous 3 articles. Elements of a strict general-relativistic modelling (equilibrium solutions of rotating perfect-fluid stars) are combined with a Newtonian rigid-body dynamics, estimates of the torques, etc., to yield a strictly general-relativistic quantity – the gravitational-wave strain. The presented model is clearly a hybrid one, but I cannot imagine a different approach right now (i.e., at the current stage of our knowledge). The gravitational-wave strain is estimated to be of the order of 10^{-24} to 10^{-23} for a pulsar located at a 1Mpc distance.

The authorship statements attached to the thesis confirm the primary role of Ankan Sur in obtaining the results reported in all four papers [1-4]. I believe that his doctoral thesis provides an important contribution to the physics of neutron stars. It should also be stated that all four research articles constituting this thesis have been published in prestigious scientific journals. Monthly Notices of the Royal Astronomical Society, in which 3 of these articles were published, belong to top journals in astronomy.

Slightly in contrast to the quality of presentation in the four articles constituting this thesis, the introductory chapter seems to be written in a hurry. In particular, not all symbols appearing in the equations of this chapter have been explained. A formula has been omitted on page 21 after the sentence `The standard models suggest (e.g. [Mas+11]):' and before ` where Λ is the ratio of the poloidal field strength to the total magnetic field strength.'

None of critical remarks listed in this review diminish my very high opinion on the quality of the presented doctoral dissertation. It proves that Anakan Sur

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can conduct an independent scientific work. It also demonstrates his expert knowledge in the physics of neutron stars.

Summing up, I consider the doctoral thesis of Ankan Sur to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

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