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Subject: Report on PhD thesis of Ankan Sur

Dear Committee,

This thesis focuses on theoretical computation of neutron star magnetic field structure, evolution, and the consequences for spin evolution and gravitational wave emission. The work is theoretical but has implications for many different aspects of neutron star astrophysics and associated observational phenomena. The origin and evolution of neutron star magnetic fields is a long-standing unsolved problem, and the thesis topic is therefore well-motivated.

The introduction provides a good overview of the state of the art regarding magnetic field modelling and observational constraints, including the recent results from the NICER mission that point towards complex multipolar fields in old recycled millisecond pulsars. There are two small corrections that should be made in the Introduction, however: Figure 1.1 should be corrected attributed to Shapiro & Teukolsky (1983); and there seems to be a missing subsection in Section 1.6 (reference is made to '2 main characteristics' but then only one subsection, on gravitational waves, follows).

The first three science chapters of the thesis focus on various questions of magnetic field evolution, explored using different simulation techniques and making different simplifications/assumptions. While they do not provide a 'definitive answer' to the exceptionally challenging question of how neutron star fields form and evolve (which would be well beyond the scope of a PhD thesis!), all contribute an interesting and significant advance to our knowledge of this area.

Chapter 2 presents non-linear MHD simulations of magnetic field evolution, for mixed toroidal/poloidal configurations, using the PLUTO code. Simulations are done using both ideal and resistive MHD, but neglecting the effects of relativity, crust physics, or superfluidity. The study is well described, and the assumptions are clear. Interesting results include the balance between toroidal and poloidal components, and the eventual development of multipolar components close to the stellar surface. This is of particular interest given NICER's recent discoveries, which require the formation, either at birth or via later evolution, of non-dipolar fields.

Chapter 3 expands upon this work, using GRMHD simulations performed with the Athena++ code to follow magnetic field evolutions for longer and at higher resolution. Again the set-up and results are well-described, and the assumptions and implications made (e.g. neglecting the crust) are clear. The only area where I would have liked to see a little more detail was on the computational cost of the simulations, since they did not reach equilibrium. The results of the GRMHD simulations are rather different to those of the previous chapter in terms of both the final field configuration and the role of turbulence. This is in part attributed to differences in boundary conditions, which is important since it points to something that clearly needs to be modelled in more detail in future simulations. Although the simulations do not reach a 'final' answer they are very useful in highlighting the various pieces of physics that will need to be included and modelled correctly in order to get to that point.

Chapter 4 presents a new computational approach that is able to generate equilibrium magnetic field configurations for a neutron star with both a crust and a superconducting core (appropriate for older colder neutron stars – the previous chapters by contrast were more relevant to hot, newborn neutron stars). The presence of both makes a substantial difference to the magnetic field structure (with the toroidal field being expelled from the core and confined to the crust), and must clearly be taken into account for older neutron stars. These findings have important implications for phenomena such as pulsar glitches and the size of any potential deformation that could be detectable by gravitational wave detectors.

The final chapter, Chapter 5, is a little different and turns to the question of the spin evolution of a newly born magnetar (a very high field neutron star), taking into account the emission of gravitational waves due to mountains formed by supernova fallback accretion. This is a topic very close to my heart (it was the topic of my first ever paper, albeit with a different gravitational wave emission mechanism!) and it was an interesting read. The model is well described, appears to contain all of the most important physics, and the consequences for gravitational wave emission are promising and well-explained. This will certainly be useful input to those preparing for the next generation of gravitational wave detectors.

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.

Yours sincerely,

Professor Anna L. Watts