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Are hypermassive neutron stars stable against a prompt collapse?

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Abstract. Differential rotation in neutron stars allows for significantly larger masses than rigid rotation. Some of those hypermassive objects are, however, unstable and collapse to a black hole immediately after formation. Yet, the exact threshold of dynamical stability is still unknown.

In our work we explore the limits on masses of neutron stars with various degrees of differential rotation which could be stable against a prompt collapse to a black hole by using turning-point (j-constant) criterion. We considered both spheroidal and quasi-toroidal differentially rotating neutron stars described by the polytropic equation of state. We find that massive configurations could be temporarily stabilized by differential rotation. Such objects are important sources of gravitational waves. Our results are a starting point for more detailed studies of stability using hydrodynamical codes.

Keywords. neutron stars, stability, supernova remnants

1. Introduction

The remnants of core-collapse supernova (CCSN) explosions can be a neutron stars (NS) with significantly differential rotation (Komatsu *et al.* 1989). NS-NS mergers can also produce a NS that is rotating differentially (Shibata *et al.* 2021).

In this work we use popular model of differential rotation of NS called KEH rotation law (or j-constant law) (Komatsu *et al.* 1989). It is consistent with numerical results obtained for CCSN remnants.

The solution space of axisymmetrical NS in equilibrium with KEH rotation law was studied extensively for polytropic equations of state (EOS) (Gondek-Rosińska *et al.* 2017; Studzińska *et al.* 2016), realistic EOS (Espino & Paschalidis 2019) and strange quark stars (Szkudlarek *et al.* 2019). Independently of the EOS, differential rotation allows for significantly higher masses than non-rotating mass limit (up to 4 times larger in some). It was shown that maximum mass of differentially rotating neutron stars and strange stars depends on the degree of differential rotation and the type of solution (Gondek-Rosińska *et al.* 2017). The highest value is obtained for moderate degree of differential rotation. Relativistic stars with masses higher than the limit for rigid rotation are called hypermassive.

It is, however, uncertain if the most massive equilibrium models are dynamically stable. They can undergo either a prompt or a delayed collapse to a black hole (BH), which can have large impact on the gravitational wave signal of the event. If a NS is temporarily stabilized by differential rotation the resulting GW emission can be much stronger than promptly collapsing NS (Giacomazzo, Rezzolla & Stergioulas 2011).

For rigidly rotating NS so-called turning-point criterion can be used to estimate the stability to axisymmetric perturbations (Friedman, Ipser & Sorkin 1988). The turning-point line is known to be a sufficient criterion of instability: for a sequence of constant angular momentum J (or baryon mass M_b) compact stars with central densities higher than configuration at the turning-point are unstable. It is also a good estimation of the real threshold of stability. Although in general there are no stability criteria found for differentially rotating NS a few dynamical calculations show that for spheroidal configuration with relatively small degrees of differential rotation the turning-point criterion line is still close to the threshold of stability (Weih, Most & Rezzola 2018).

In this work we study equilibrium sequences of differentially rotating neutron stars described by the polytropic equation of state. Using the turning-point criterion for the broad ranges of masses and degrees of differential rotation, including both spheroidal and quasi-toroidal configurations we find the region of stable configurations.

2. Calculations and results

We use highly accurate relativistic and stable code *FlatStar* (Ansorg *et al.* 2009) to calculate sequences of differentially rotating equilibrium configurations with KEH rotation law and polytropic EOS with $\Gamma = 2$.

For different degrees of differential rotation $\widetilde{A}$ and for types A and C (according to classification of Ansorg *et al.* 2009) we constructed multiple sequences of fixed baryon mass M_b and sequences of fixed angular momentum J. We studied sequences for $\widetilde{A} =$ 0, 0.5, 0.7, 0.77, 1.0. Our sample of configurations covered large range of masses up to the limits found by Gondek-Rosińska *et al.* (2017). For each sequence of constant M_b (or J) we select the configuration of a minimum (or, respectively, maximum) gravitational mass M. For given $\widetilde{A}$ selected points create two turning-point lines (M_b-const and J-const).

For rigid rotation the J-const turning-point line overlap with M_b-const turning-point line. It's not the case for differential rotation – the M_b-const turning points are shifted towards lower central (maximal) densities. For this study we used M_b-const turning points, which gives more strict estimation of stability.

For each considered degree of differential rotation $\widetilde{A}$ we used the M_b-const turning-point line as an estimation of the onset of instability and compared it with mass limit. For all degrees of differential rotation the maximum mass was located in the region corresponding to the stable configurations. Our calculations show that the most massive differentially rotating NS of type A and C (with masses up to 2.5 times larger than the TOV limit) could be stable against a prompt collapse to BH. This result should be verified by hydrodynamical calculations in full general relativity.

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