Stability properties of differentially rotating neutron stars

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Astrophysical context

Differential rotation may play important role in:

- NS-NS mergers
- Massive stellar core collapse

Bartos, Brady, Marka 2013
Outline:

- Relativistic FlatStar code for neutron stars (NS) and strange quark stars (SQS) equilibria
- Maximum mass of differentially rotating NS
- Multiple types of solutions
- Stability properties of differentially rotating NS
FlatStar code

- Relativistic multidomain spectral code for stationary, axisymmetric models of differentially rotating NS and SQS
- Highly accurate and stable
- Can calculate configurations, which are difficult to obtain for other codes

Example numerical grid for highly flattened configuration
Equilibrium model for differentially rotating NS

Example rotation curve in equatorial plane

- j-const rotation law (consistent with core-collapse results)
  \( u^t u_\phi = F(\Omega) = A^2(\Omega_c - \Omega) \)
  (Komatsu et al. 1989)

- A is length describing degree of differential rotation, i.e.
  \( \Omega(r = A) = \frac{\Omega_c}{2} \)
  \( \tilde{A} = \frac{r_e}{A} \)

- polytropic EOS: \( P = K \rho^\Gamma \)
  (e.g. \( \Gamma = 2 \))
Effects of rotation on maximum allowed NS mass

- No rotation: \( M_{\text{max}} = M_{\text{TOV}} \)
- **Rigid** rotation: increase of \( M_{\text{max}} \) by 20\% (e.g. Cook et al. 1994)
Effects of rotation on maximum allowed NS mass

- No rotation: \( M_{\text{max}} = M_{\text{TOV}} \)
- **Rigid** rotation: increase of \( M_{\text{max}} \) by 20\% (e.g. Cook et al. 1994)
- **Differential** rotation: \( M_{\text{max}} \) depends on \( \tilde{A} \) (Baumgarte et al. 2000)

Upper limit on rest mass for different degrees of differential rotation (Gondek-Rosińska et al. 2017)
Maximum mass of differentially rotating NS: existence of type A and B

Coexisting types A and B for $\tilde{A} = 0.7$ (Gondek-Rosińska et al. 2017)
Examples of four types of solutions (Studzińska et al. 2016)

Type A with $\tilde{A} = 0.7$

Type B with $\tilde{A} = 0.8$

Type C with $\tilde{A} = 1.1$

Type D with $\tilde{A} = 1.1$
Maximal masses for differentially rotating NS depend on the degree of differential rotation and solution type, for polytrope with $\Gamma = 2$ (Gondek-Rosinska et al. 2017)
Effect of EOS on $M_{\text{max}}$

Universal feature for different polytropes (Studzińska et al. 2016) confirmed also for realistic EOS (Espino et al. 2019) and for SQS (Szkudlarek et al. 2019)
Are massive, differentially rotating neutron stars stable against prompt collapse to BH?
Stability criteria for uniform rotation

Turning-point criterion (see Friedman, Ipser and Sorkin, 1988)
Is the turning-point criterion valid for differential rotation?

Example const-J sequences for differential rotation with $\tilde{A} = 0.77$ (Weih, Most and Rezzolla 2017)
Universal J-$M_b$ relation for low J

Quasi-universal relations for turning points
Summary

- Four types of equilibrium solutions for NS and SQS (Ansorg et al. 2009)
- Massive NS can be stabilized by differential rotation
- $M_{\text{max}}$ depends on degree of differential rotation and type of solution (Gondek-Rosińska et al. 2017), similar for realistic EOSs (Espino et al. 2019) and SQS (Szkudlarek et al. 2019)
- No simple stability criterion
- Quasi-universal relations for turning points
- Potential source of gravitational waves at collapse (Giacomazzo et al. 2011)
Gravitational-wave amplitudes $h_+$ and $h_x$ for two collapses, left: $J/M^2 < 1$, right: $J/M^2 > 1$ (Giacomazzo et al 2011)
Const-$M_b$ turning points

Turning points $J=\text{const}$ and $M_b=\text{const}$ compared with stability