Equation of state of cold rapidly rotating neutron stars and the effects of the Keplerian sequence

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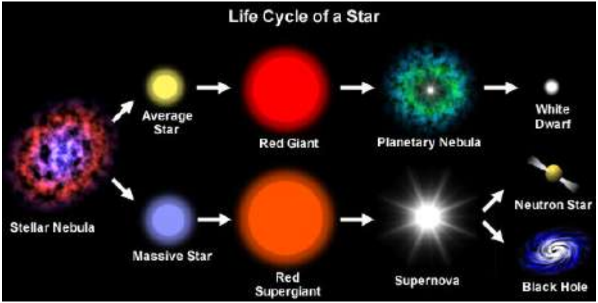
Stellar Remnants

The remnants of supernova collapse, can take one of the three forms

- White Dwarf
- Neutron Star
- Black Hole



Stellar Remnants

The remnants of supernova collapse, can take one of the three forms

- White Dwarf
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Neutron Star

- Mass: 1.4-2.5 $M_{\odot}$
- Eq. Radius: 10-15 km
- Mean density: 4×10^{14} gr/cm^3
- Frequency: up to 2.2 kHz

The fastest observed rotating neutron star is at 716 Hz

From Static to Rapidly Rotating Neutron Stars

Static Configuration

- Space-time metric :
  $ds^2 = e^{\nu} dt^2 - e^{\lambda} dr^2 - dr^2 - r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right)$
- Perfect fluid : $T_{\mu\nu} = (\epsilon + p)\, u_\mu u_\nu + p g_{\mu\nu}$
- TOV system $\rightarrow$ $m(r)$, $p(r)$, $\epsilon(r)$, etc.

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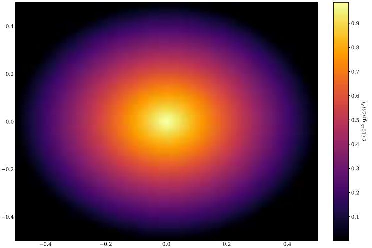
Rotating Configuration

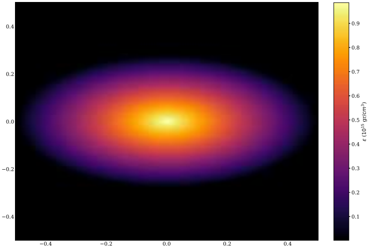
- Space-time metric :
  $ds^2 = e^{\nu} (1 + 2h)\, dt^2 - e^{\lambda} \left[1 + \frac{2m}{r - 2M_0} \right] dr^2 -$
  $r^2 (1 + 2k) \left[d\theta^2 + \sin^2 \theta \left(d\phi - \omega dt \right)^2 \right] + O\left(\Omega^3 \right)$
- Perfect fluid : $T_{\mu\nu} = (\epsilon + p)\, u_{\mu} u_{\nu} + p g_{\mu\nu}$
- TOV system $\rightarrow m(r),\ p(r),\ \epsilon(r),\ \omega(r)$ etc.

From Static to Rapidly Rotating Neutron Stars

Differences between the static and rotating configuration

- $M_{max}^{st} < M_{max}^{rot}$
- $R_{eq,max}^{st} < R_{eq,max}^{rot}$
- $\epsilon_c^{st} > \epsilon_c^{rot}$
- The existence of the angular velocity and the Kerr parameter (only in rotating configuration)





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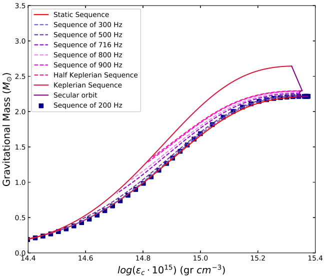
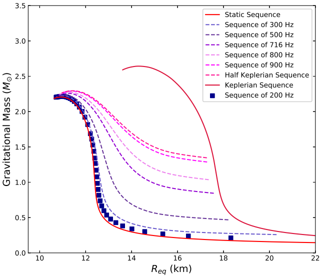
The knowledge of the maximum mass and the maximum frequency, can help us:

- Identify a compact object as a Black Hole
- Constrain the high density part of the Equation of State

From Static to Rapidly Rotating Neutron Stars

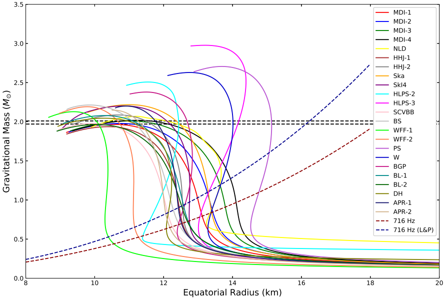




APR-1 Equation of State

From Static to Rapidly Rotating Neutron Stars

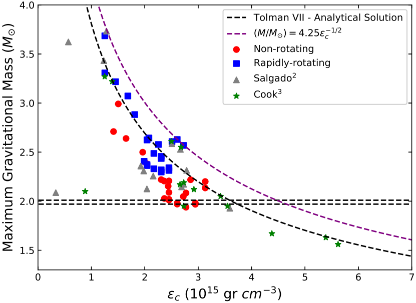
- We employ a total of 23 realistic EoS for neutron star matter, based on various theoretical nuclear models
- They satisfy the observed limit of $M = 1.97 \pm 0.04 M_{\odot}$ and $M = 2.01 \pm 0.04 M_{\odot}$
- They satisfy the observed frequency 716 Hz limit introduced by Lattimer & Prakash[1]



[1] J. M. Lattimer and M. Prakash, Science 304, 536 (2004), ISSN 0036-8075, URL https://science.sciencemag.org/content/304/5670/536

From Static to Rapidly Rotating Neutron Stars

- $M^{st}_{max} < M^{rot}_{max}$
- $R^{st}_{eq,max} < R^{rot}_{eq,max}$
- $\epsilon^{st}_{c} > \epsilon^{rot}_{c}$



[2] M. Salgado, S. Bonazzola, E. Gourgoulhon and P. Haensel, Astron. Astrophys. Suppl. Ser. 108, 455-459 (1994)
[3] Gregory B. Cook, Stuart L. Shapiro and Saul A. Teukolsky, The Astrophysical Journal, Vol. 424, 823-845 (1994)

Effects of the Keplerian Sequence - Maximum frequency

- Determines the maximum rotation rate
- Depends on the gravitational mass of the star $\rightarrow$ EoS dependent
- $f_{max}(M_{max}, R_{eq,max}) = c \left(\frac{M_{max}}{M_{\odot}}\right)^{1/2} \left(\frac{10km}{R_{eq,max}}\right)^{3/2}$

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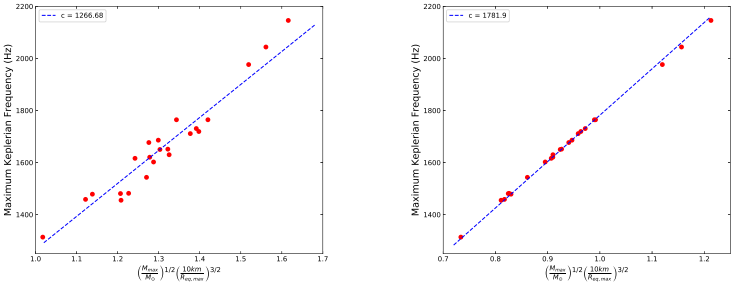
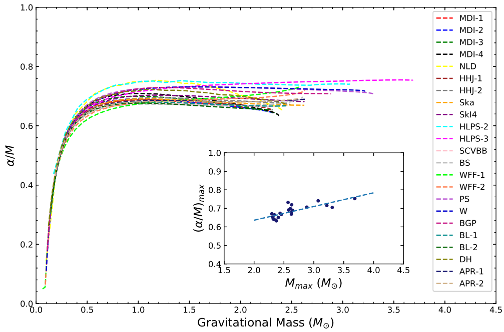


Effects of the Keplerian Sequence - The Kerr parameter

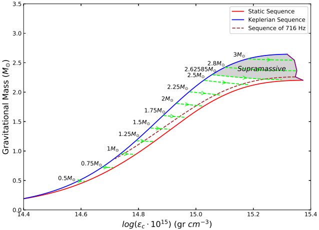
- $j = cJ/(GM^2)$
- $(\alpha/M)_{max} \approx 0.75$
- $(\alpha/M)_{max} = 0.074 M_{max} + 0.488$

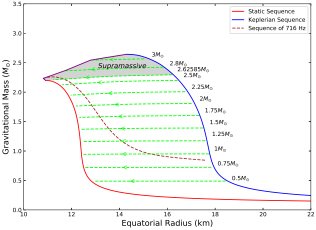
$$(\alpha/M)^{B.H.}_{max} \approx 0.998$$



Rest Mass Sequences

- Time evolutionary sequences
- Normal & Supramassive

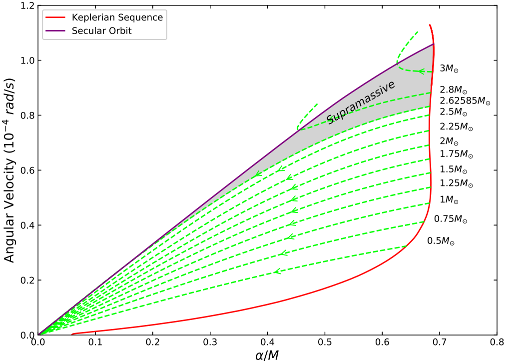




APR-1 Equation of State

Rest Mass Sequences

- Prior to collapse the star spins up
- Gravitation collapse



APR-1 Equation of State

Conclusions

- The M_{max}^{rot} and f_{max} can constrain the EoS at high densities
- The M_{max}^{rot} can provide us with the ultimate density of cold baryonic matter
- The Kerr parameter determines the final fate of the collapse of a rotating compact star
- The calculation of Kerr parameter can help us to identify a compact object as a black hole and possibly imply the existence of universal limiting value of the neutron star compactness
- Supramassive curves may provide an observable precursor to gravitation collapse to a black hole and constrain the angular momentum

Thank you for your attention!