Constraints on High-Density Matter From Observations of Neutron Stars

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High-density matter in astrophysics.

Relation of macroscopic quantities to microphysics.

History of astrophysical EOS constraints.

Constraints from low-mass X-ray binaries.

Future constraints and needs.

High-Density Matter in Astrophysics

Formation of primordial black holes.

Dark horse dark matter candidate.

Gamma-ray burst models.

Gravitational radiation waveforms from NS inspiral.

LIGO, VIRGO, etc.

Understanding of core-collapse supernovae.

Detection of GR phenomena around neutron stars.

Innermost stable circular orbit (ISCO).

Macroscopic Indicators of Microphysics

The gross structure of the NS is affected by the state of matter beyond nuclear saturation density.

Maximum mass.

Soft EOS $\Rightarrow$ low $M_{\rm max}$; hard $\Rightarrow$ high $M_{\rm max}$.

Precise mass and radius for a single star.

Maximum spin rate.

Mass-shedding limit.

Soft EOS $\Rightarrow$ high $\nu_{\rm max}$; hard $\Rightarrow$ low $\nu_{\rm max}$

Moment of inertia for a given mass.

Thermal emission at a given age.

Exotic components $\Rightarrow$ more $\nu, \bar{\nu}$, lower T.

History of EOS Constraints

Binary pulsar measurements.

Very precise masses, but only $M \approx 1.44\,M_\odot$.

Eliminates only unrealistically soft EOS.

Millisecond pulsars.

Highest known spin rate is 642 Hz.

Eliminates only unrealistically hard EOS.

Thermal emission.

Current modeling is too imprecise.

Mass of NS in accreting binaries.

Larger M because of accretion.

Cyg X-2: $M > 1.88\,M_\odot$ (95%) from light curve.

Vela X-1: $M = 1.86 \pm 0.17\,M_\odot$ (Barziv et al. 2001).

Observations of Low-Mass X-ray Binaries

$M < M_\odot$ companion $\Rightarrow$ weakly magnetic NS.

Not known why!

Thus, X-ray emission tells us about spacetime, NS properties.

Look for signatures of orbital motion, ISCO.

Cutoff in orbital frequencies at $\nu_{\rm ISCO}$?

Kilohertz brightness oscillations.

Yield constraints on M, R.

First astrophysical elimination of hard EOS.

Evidence for ISCO

Lower limit to $r_{\rm orb}$ is $r_{\rm ISCO}$

Inside $r_{\rm ISCO}$, rapid inspiral $\Rightarrow$ low coherence.

Thus, upper limit to $\nu_{\rm QPO}$ is $\nu_{\rm ISCO}$.

Observed $\nu_{\rm QPO}$ increases with $\dot{M}$.

Therefore, expect reproducible rollover at $\nu_{\rm ISCO}$.

4U 1820–30: consistent rollover seen at 1100 Hz.

Major discovery: first evidence of ISCO.

Including frame-dragging, implies $M = 2.15\, M_\odot$!

Future Constraints and Needs

Future constraints from NS observations.

Better mass estimates of more NS in binaries.

Spectral line measurements in cooling NS.

Future high-area timing instrument.

Oscillation waveforms would give precise M, R.

Quantitative tests of strong-gravity GR.

For supernova, gamma-ray burst, and NS merger calculations, the astrophysical community needs more tabulated EOS for hot as well as for cold NS.