The Physics of Neutron Stars

Lattimer & Prakash, SCIENCE 304, 536–542 (2004)

Presented by
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The building blocks (A very short review of the Particle Zoo)

QUARK	fundamental particle	up, down, strange, charm, top, bottom
LEPTON	fundamental particle	electron, muon, tauon neutrinos
HADRON	particle composed of quarks	baryons, mesons
BARYON	particle with odd number of quarks	uud: proton udd: neutron
MESON	particle with even number quarks	π+ ($u\bar{d}$), π- ($\bar{u}d$), ...

STRONG	attraction between quarks	binds atomic nuclei
WEAK	changes flavor of quarks and leptons	β decay
EM	attraction between charged particles	binds atoms
GRAVITY	attraction between massive particles	binds celestial bodies

Lattimer & Prakash: The Physics of Neutron Stars (2004)

Neutron stars — A brief introduction

MASS ~1.5 solar masses   RADIUS ~12 km   DENSITY 5–10 times higher than atomic nuclei

ORIGIN evolution of massive stars

COMPOSITION mostly neutrons (+exotic particles)

e.g. strangeness-bearing baryons
mesons
deconfined quarks

TYPES "normal" or "strange quark matter" (SQM)

"normal"	"strange quark matter" (SQM)
hadronic exterior	bare quark-matter surface
surface P, ρ vanish	surface P vanishes, but high surface ρ
bound by gravity	bound by strong force
	emit mainly in hard X-rays and γ-rays
	hypothetical

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Outline

- Formation
- Structure and Composition
- Evolution
- Observation
- Future Research

Formation of Neutron Stars

①
GRAVITATIONAL COLLAPSE
of a massive star's Fe-Ni core.
→ lepton-rich matter
→ compression to nuclear density
→ shockwave (accelerated by neutrino pressure) strips the mantle → Supernova

②
PROTO-NEUTRON STAR
rapidly shrinks due to diminishing neutrino pressure.
→ neutrinos escape within ~10s
(obs. SN 1987A)

③
CORE HEATING
due to electron-proton combination.
→ T ~ 10^{11} K
→ duration: ~10–20s

④
COOLING
due to steady neutrino emission.
→ The star becomes transparent to neutrinos after ~50s
NEUTRON STAR

Black Hole formation channels

(I) Mass falls through the shock before lift-off.
ACCRETION

(II) Collapse once electron and neutrino pressure is removed.
DELEPTONIZATION

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NEUTRON STAR

Mass limits

MAX $3\ M_\odot$ (theoretical)
$1.44\ M_\odot$ (observed)

MIN $0.1\ M_\odot$ (theoretical)
$1\ M_\odot$ (evolution)

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Structure of Neutron Stars

Mass continuity

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi\rho r^2$$

Hydrostatic equilibrium

$$\cancel{\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm(r)\rho}{r^2}} \longrightarrow \frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{G(m(r) + 4\pi r^3 P/c^2)(\rho + P/c^2)}{r(r - 2Gm(r)/c^2)}$$

Equation of state

$$P = P(\rho, \cancel{T})$$

UNKNOWNS	$m(r)$, $P(r)$, $\rho(r)$
ASSUMPTION	EOS
SOLUTION	numerical M–R relation

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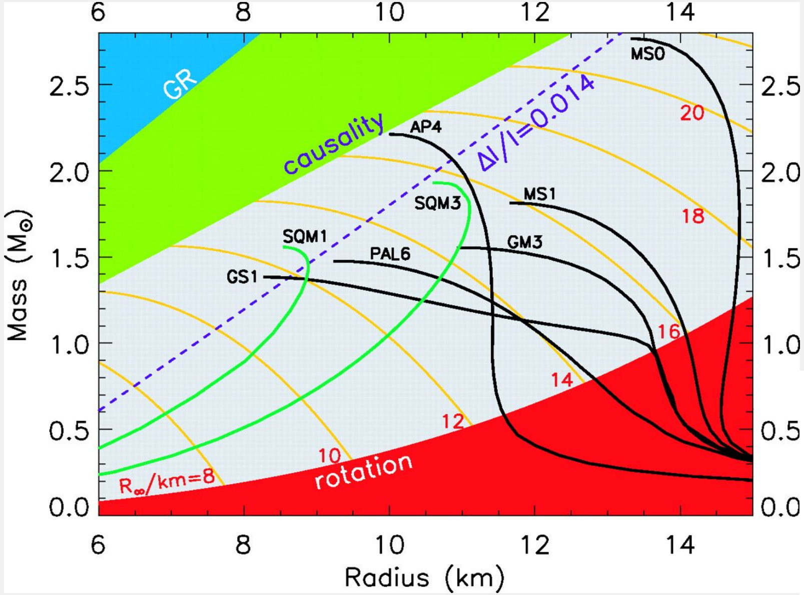
Structure of Neutron Stars



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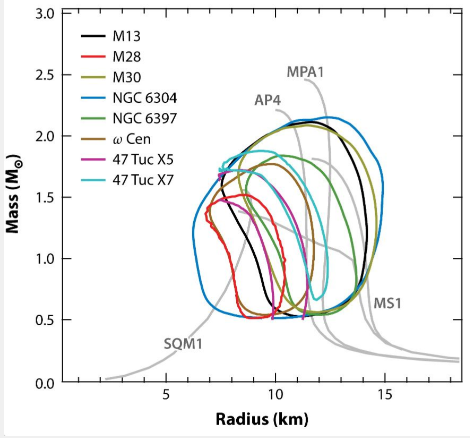

Özel & Freire (2016)

Equations of State

Symbol	Reference	Approach	Composition
FP	Friedman & Pandharipande (1981)	Variational	*np*
PS	Pandharipande & Smith (1975)	Potential	$n\pi^0$
WFF(1–3).......	Wiringa, Fiks & Fabrocine (1988)	Variational	*np*
AP(1–4)	Akmal & Pandharipande (1997)	Variational	*np*
MS(1–3).........	Müller & Serot (1996)	Field theoretical	*np*
MPA(1–2).......	Müther, Prakash, & Ainsworth (1987)	Dirac-Brueckner HF	*np*
ENG	Engvik et al. (1996)	Dirac-Brueckner HF	*np*
PAL(1–6)	Prakash et al. (1988)	Schematic potential	*np*
GM(1–3)	Glendenning & Moszkowski (1991)	Field theoretical	*npH*
GS(1–2)	Glendenning & Schaffner-Bielich (1999)	Field theoretical	*npK*
PCL(1–2)	Prakash, Cooke, & Lattimer (1995)	Field theoretical	*np*HQ
SQM(1–3).......	Prakash et al. (1995)	Quark matter	Q (*u*, *d*, *s*)

Note.—"Approach" refers to the underlying theoretical technique. "Composition" refers to strongly interacting components (*n* = neutron, *p* = proton, H = hyperon, K = kaon, Q = quark); all models include leptonic contributions.

Lattimer & Prakash (2001)

The quest for the Equation of State

- The EOS inside neutron stars is non-trivial → important for fundamental physics
- Conditions are difficult to reproduce in the laboratory.
  - Nuclear matter is about 50% neutrons, for NS this is closer to 99% neutrons
- Large uncertainties:
  - Factor 6 of variation in pressure at nuclear density for neutron-dominated matter!
  - Leads to almost 50% uncertainty in predictions of radii.
- M–R relation could be constrained from rotation
  - Leads to better constraints on the EOS

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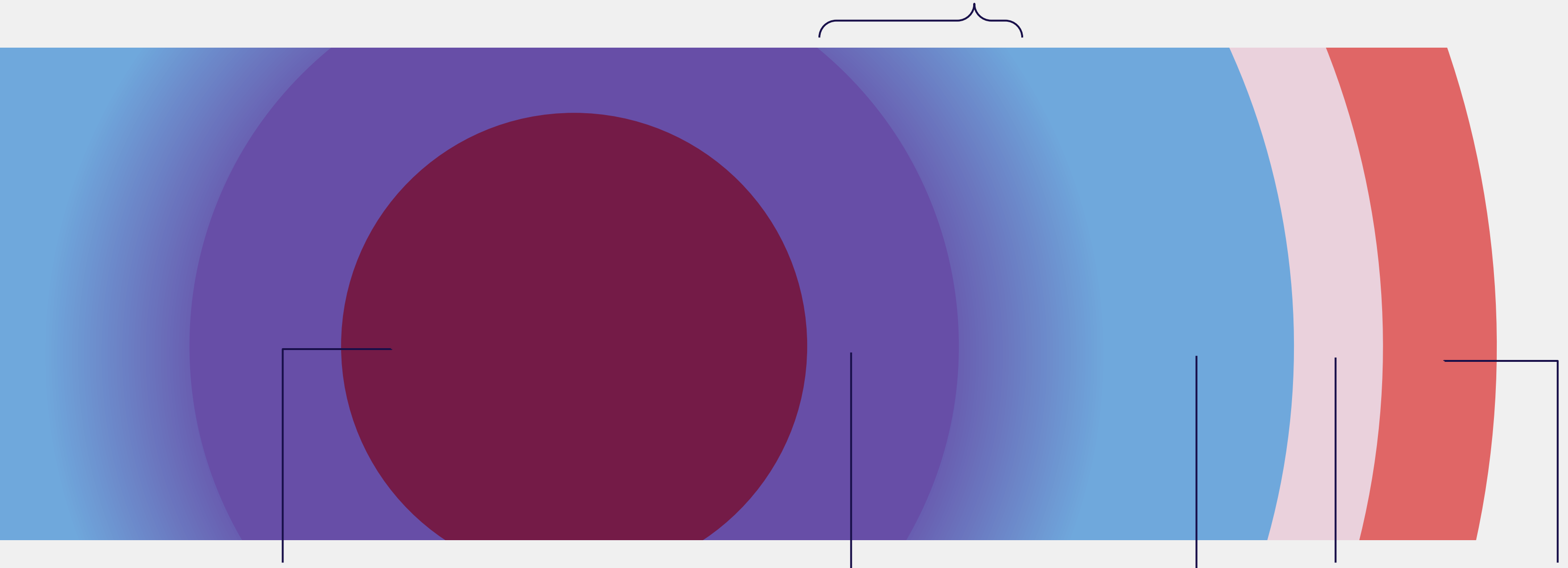
Internal layers



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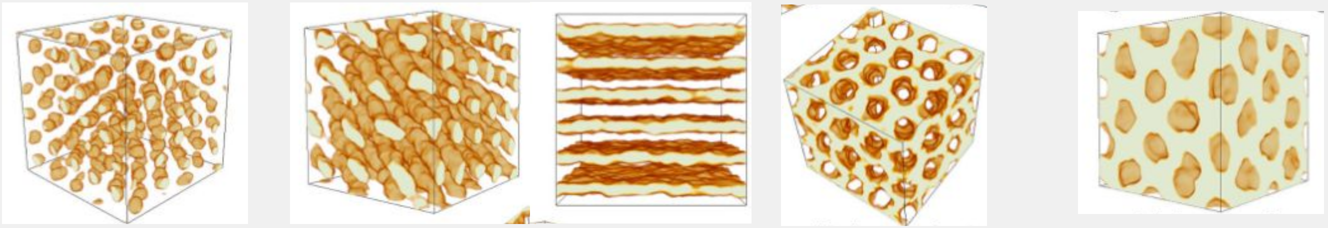
Nuclear pasta

Meatballs Gnocchi Spaghetti Lasagna Ziti Ravioli Sauce



Schneider et al. (2013)

CRUST → CORE

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Evolution (cooling)

- Heat transport into the interior by electron conduction
  - Neutrino losses from interior.
- After 10~100 years, the neutron star becomes isothermal
- Photoemission in X-rays ($T_{eff} \sim 1\% \ T_{interior}$)
- Neutrino emission dominates for about 300 000 years
- Urca-processes:
  - Direct: $n \rightarrow p + e^- + \bar{\nu}_e$ | $p \rightarrow n + e^+ + \nu_e$
  - Modified: $n + (n,p) \rightarrow p + (n,p) + e^- + \bar{\nu}_e$ | $p + (n,p) \rightarrow n + (n,p) + e^+ + \nu_e$ (conserve linear momentum)
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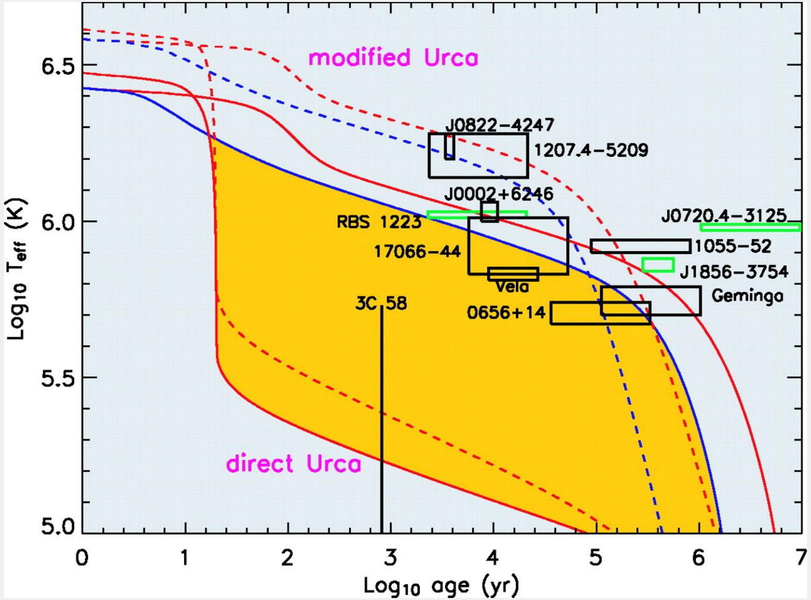
- Central quantity: symmetry energy function $S_\nu(n)$:

$$E(n, x) = E(n, x=0.5) + S_\nu(n)\,(1-2x)^2$$

Evolution (cooling)



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Observations

MASS
most accurate from pulsars in binaries
can determine *both* masses in the binary due to relativistic effects
(e.g. Shapiro time delay)

also from accretion in X-ray binaries

THERMAL EMISSION
mostly overshadowed by non-thermal emission (magnetic effects)

a few observations exist, probably at around 300 000 – 1 000 000 K

R is difficult to determine, since $F=\sigma T_{eff}^4(R/d)^2$ must be corrected by redshift, which is itself M and R dependent.

Neutron stars are not black bodies!

optical emission deficit observed (compared to X-ray)

consistent with heavy-ion atmospheres, but narrow spectral features are absent...

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Future prospects

- Accelerator experiments to determine nuclear physics (e.g. Lattimer 2023)
- Neutrino observations of supernovae
- Gravitational wave detections
    - Multimessenger detection of GW170817 (LIGO coll. et al. 2017, 2021)
- Detailed models of cooling mechanisms (e.g. Sales et al. 2020)
- Signatures of chemical composition (e.g. Levan et al. 2023)

Questions