NEUTRON STARS:
ASTROPHYSICAL LABORATORIES FOR NUCLEAR PHYSICS

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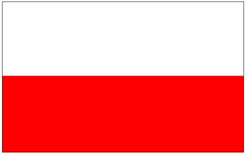
October 25, 2016

Astro-PF
Polish-French collaboration in astrophysics

comp star

NATIONAL SCIENCE CENTRE
POLAND

Poland



Source : Wikipedia

Some data:

- parliamentary republic
- president: Andrzej Duda
- prime minister: Beata Szydło
- capital: Warsaw
- 3 times larger than Portugal
- 4 times more populated than Portugal
- currency: złoty
- religion: mostly Roman Catholicism

Polish

- slavic language but latin alphabet
- hello: dzień dobry
- thank: dziękuję
- goodbye: do widzenia

Warsaw

Stare miasto (Wikipedia)

Pałac Kultury i Nauki (Wikipedia)

NewCompstar conference on neutron stars and supernovæ

last week of March 2017, in Warsaw ☺

Neutron stars: general aspects

Discovery of neutron stars (NSs)

From theoretical predictions . . .

Yakovlev et al., arXiv:1210.0682 (2012)

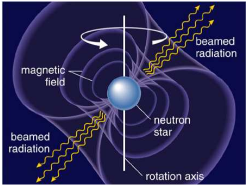
- Feb. 1931 : anticipation of the idea of NSs by Lev Landau :
  - calculation of the maximum mass of white dwarfs;
  - prediction the existence of dense stars which look like giant atomic nuclei.
- end of Jan. 1932 : experiments by Chadwick and discovery of the neutron.
- Feb. 27, 1932 : publication of Chadwick's paper.
- Feb. 29, 1932 : publication of Landau's paper.
- Dec. 15, 1933 : Baade & Zwicky:
  "*supernovæ represent the transitions from ordinary stars to neutron stars, which in their final stages consist of extremely closely packed neutrons*".

Discovery of neutron stars (NSs)

. . . to observations

Haensel et al.'s book (2007)

- 1967 : observation by chance by Bell (Hewish's graduate student) of very stable radio pulses with $P = 1.3373012$ s
  $\rightarrow$ artificial origin, created by space satellites or extraterrestrial civilization?
- Feb. 24, 1968 : publication of the paper in Nature:
  - the source is called "pulsar" meaning "Pulsating Source of Radio",
  - the source might be an oscillating white dwarf or NS.
- May 1968 : Gold, Nature : pulsar = rotating NS.



- 1974 : Nobel Prize to Hewish (only) for the discovery of pulsars.

Period of the pulses = spin period P of the pulsar.

All PSRs are NSs but not all NSs are seen as PSRs.

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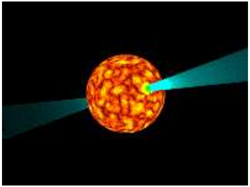

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What is a neutron star?

Origin

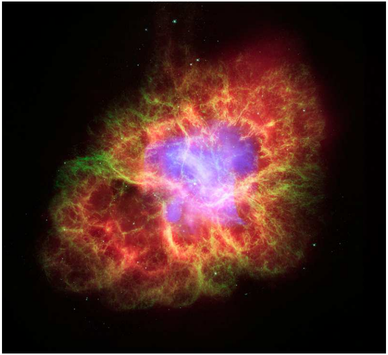
Remnant from the gravitational collapse of a $\sim$ 10 $M_\odot$ star during a Type II, Ib, Ic supernova event.

Properties

- mass $M \sim 1.4\ M_\odot$ ($M_\odot = 10^{30}$ kg),
- radius $R \sim 10$ km,
- compactness $\frac{GM}{Rc^2} \sim 0.2$,
- average density $\bar{\rho} \sim 10^{18}$ kg m^{-3},
- magnetic field $B \sim 10^4 - 10^{14}$ T.

$\Rightarrow$ relativistic objects sustained by the strong interaction.

Crab Nebula hosting a pulsar



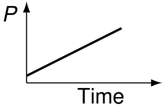
Credits : NASA/ESA.

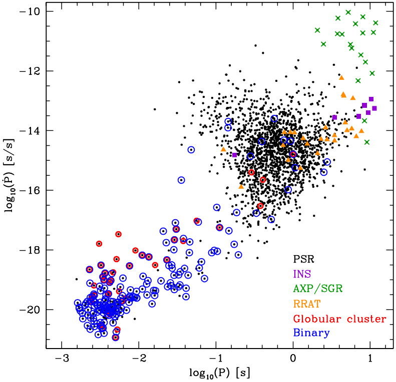
Observations

$\sim$ 2000 NSs from radio to γ-rays, a majority as radio pulsars.
$\sim$ 5% of them in a binary with a companion star.

Pulsar population

NSs undergo a regular spin-down ie. an increase $\dot{P}$ of their spin period P :





$P - \dot{P}$ diagram.
Data from ATNF pulsar catalog.

Several types of emission

- PSR: radio or γ-ray pulsars,
- INS: X-ray pulses, no radio pulses,
- AXP/SGR: bursts observed in X- or γ-rays,
- RRAT: radio bursts.

Toy model

Magnetic dipole :

- spin-down due to emission of electromagnetic radiation.

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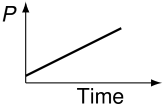

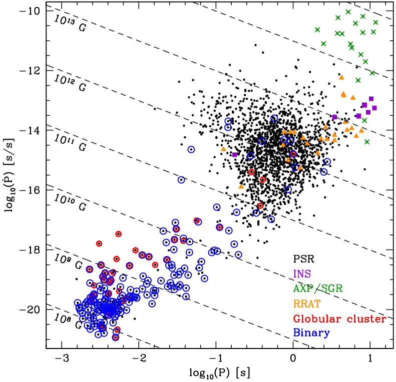

$P - \dot{P}$ diagram.
$I = 10^{45}$ g cm^2, $R = 10$ km.

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Magnetic dipole :

- spin-down due to emission of electromagnetic radiation.
- estimate of the magnetic field :

$$B = \left(\frac{3c^3 I}{8\pi^2 R^6} P\dot{P} \right)^{1/2}$$

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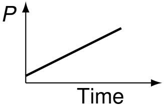

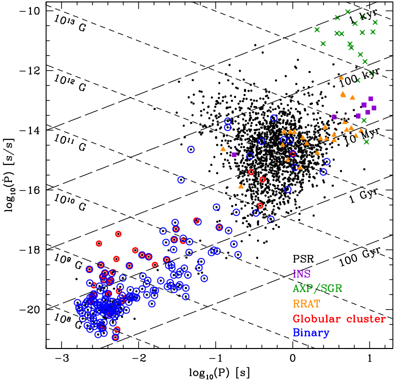

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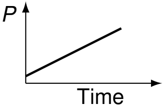

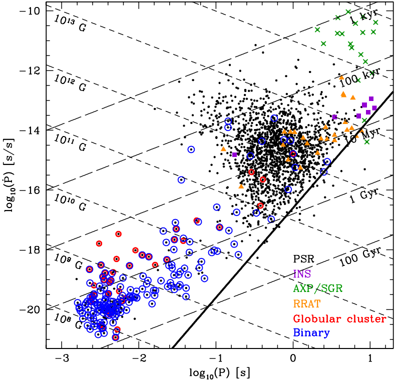

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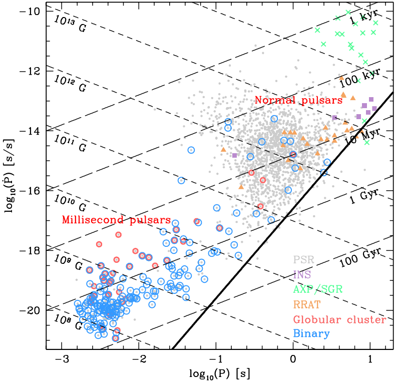
- estimate of the age : $\tau = \frac{P}{2\dot{P}}$
- (model-dependent) death line : below the line, electromagnetic emission stops.

Pulsar population



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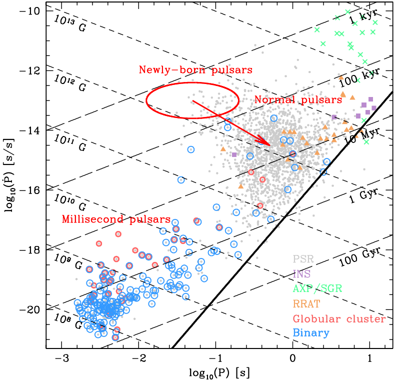
Two main types of pulsars

	Normal	Millisecond (MSP)
P (s)	1	0.03
B (G)	10^{12}	10^{8}
τ (yrs)	10^{7}	10^{9}

Pulsar population



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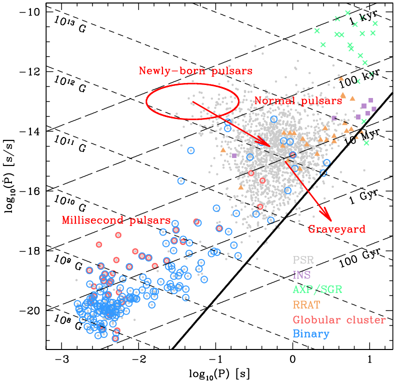
Normal pulsars

NSs born fastly rotating, spun down by the radio emission until they cross the death line.

Pulsar population



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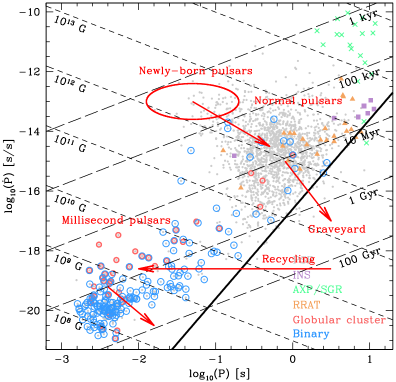

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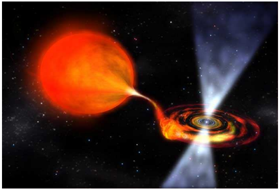
Normal pulsars

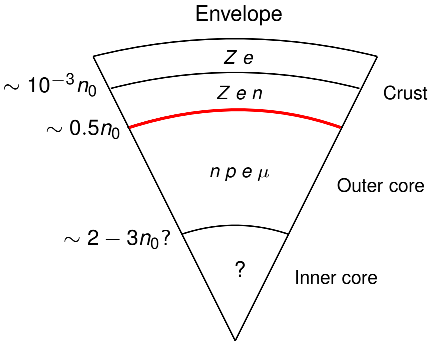
NSs born fastly rotating, spun down by the radio emission until they cross the death line.

Millisecond pulsars

Old pulsars rejuvenated by the accretion of matter from a binary companion.



Structure



Envelope

$Z\ e$

$\sim 10^{-3} n_0$

$Z\ e\ n$

Crust

$\sim 0.5 n_0$

$n\ p\ e\ \mu$

Outer core

$\sim 2-3 n_0$?

?

Inner core

Nuclear saturation density: $n_0 = 0.16\ \mathrm{fm}^{-3}$

Problem

NS matter not accessible in terrestrial laboratories . . .

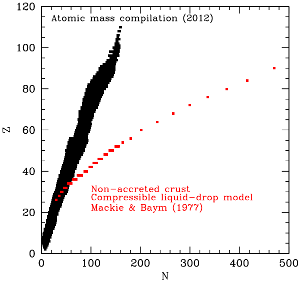
Envelope

- Plasma whose composition determines the spectrum of the NS emission.

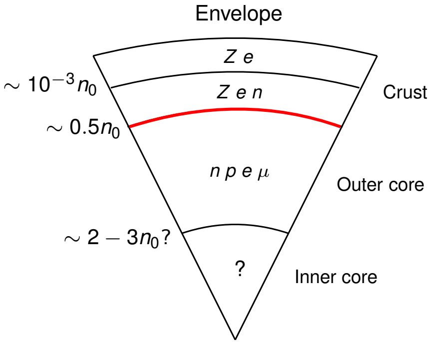
Crust

- Gas of electrons,
- lattice of neutron-rich ions,
- at larger densities free neutrons (superfluid?).

Nuclei in lab. vs. NS crust



Structure



Nuclear saturation density: $n_0 = 0.16\ \text{fm}^{-3}$

?=

- nucleons,
- hyperons (baryons with a least one *s* quark),
- quark matter (deconfined *d*, *u* and *s*),
- pion or kaon condensation, ...

Envelope

- Plasma whose composition determines the spectrum of the NS emission.

Crust

- Gas of electrons,
- lattice of neutron-rich ions,
- at larger densities free neutrons (superfluid?).

Outer core

- Free neutrons and protons (superfluid?),
- electrons,
- muons.

Inner core

- ?

Equation of state

Mystery : equation of state (EoS)

- Describes the composition and properties of NS matter;
- $P(n)$ with P the pressure and n the baryon density.

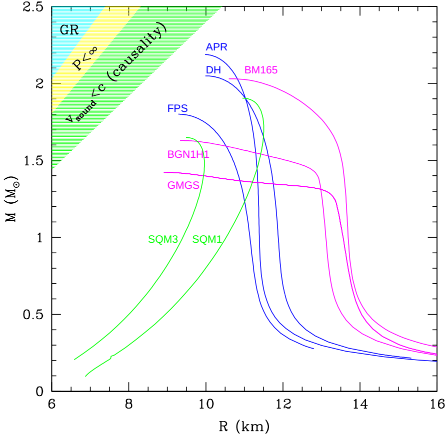
NS matter

Many-body system of strongly-interacting particles (e, p, n, μ, more?) at zero temperature (thermal energy $\ll$ nucleon Fermi energy).

Two approaches:

- phenomelogical models with effective interactions with parameters adjusted to nuclear and astrophysical quantities,
- ab-initio approaches: 'solving' the many body problem starting with 2 (and 3)-body interactions.

Mass-radius diagram



EoSs for nucleonic matter (blue), exotic matter (pink) and strange quark matter (green).

Equation of state

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NS structure

A given EoS

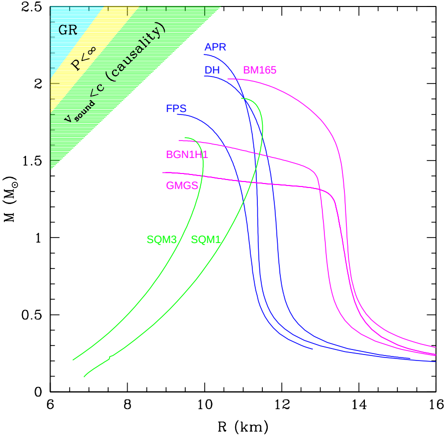
\+ hydrostatic equil. in GR (TOV equations)

= a specific mass-radius (M-R) relation.

Key point

How to constrain the EoS and thus the properties of the nuclear interaction at large densities thanks to NS observations ?

Mass-radius diagram



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Astrophysical constraints on the EoS

Astrophysical constraints: mass

Keplerian orbital elements

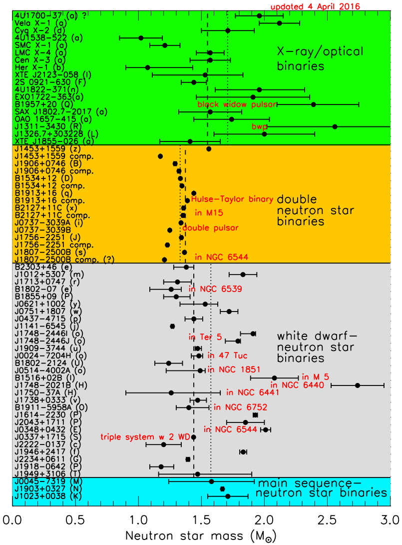
- orbital period P_b,
- time of periastron passage T_0,
- eccentricity e,
- projected semi-major axis $x(i)$,
- angle of periastron ω;

$\Rightarrow$ mass function $f_1(M, m_c, i)$.

Relativistic phenomena

- precession of periastron,
- orbital decay,
- gravitational redshift and time dilation,
- Shapiro delay;

$\Rightarrow$ 2 additional quantities.



Astrophysical constraints: mass

Theory

- each EoS has a maximum mass $M_{\rm max}$;
- $M_{\rm max} \geq M_{\rm max}^{\rm obs}$.

PSR J1614-2230

Demorest et al., Nature (2010)
Shapiro delay : *r* & *s* parameters (nearly edge-on binary system)

$$M_{\rm max}^{\rm obs} = 1.97 \pm 0.04 \ {\rm M}_\odot.$$

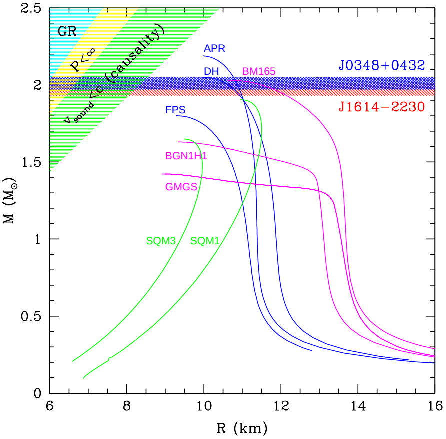
PSR J0348+0432

Antoniadis et al., Science (2013)

$$M_{\rm max}^{\rm obs} = 2.01 \pm 0.04 \ {\rm M}_\odot$$

but model-dependent . . .

Mass-radius diagram



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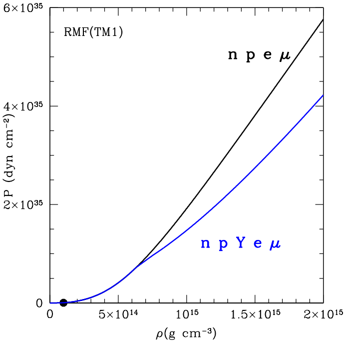
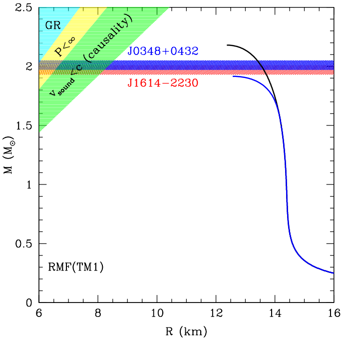
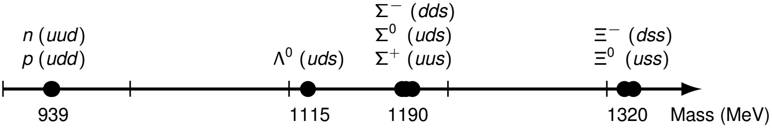
Astrophysical constraints: mass

Equation of state



$M - R$ plot





Astrophysical constraints: mass

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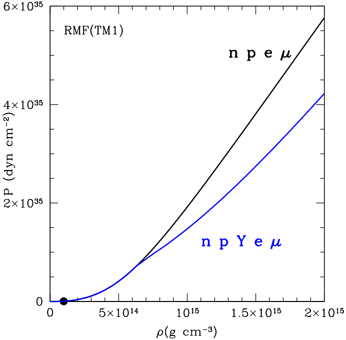

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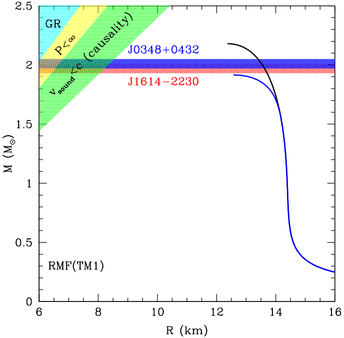


Hyperons

- reduce the pressure in the inner core. ie. softening of the EoS;
- reduce the maximum mass.

Claims that $M_{\max} \geq 2\,M_\odot$ rules out hyperonic EoSs . . .
but it is possible to build some hyperonic EoS with $M_{\max} \geq 2\,M_\odot$.

Astrophysical constraints: redshift

Surface gravitational redshift z_g

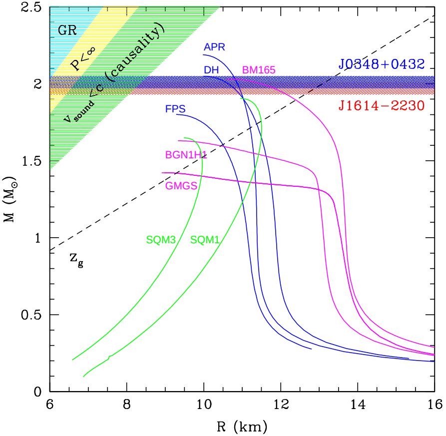
$$\frac{M}{R} = \frac{c^2}{2G}\left[1 - (1 + z_g)^{-2}\right]$$

If M known → a single point in the (M, R) plane.

EXO 0748-676

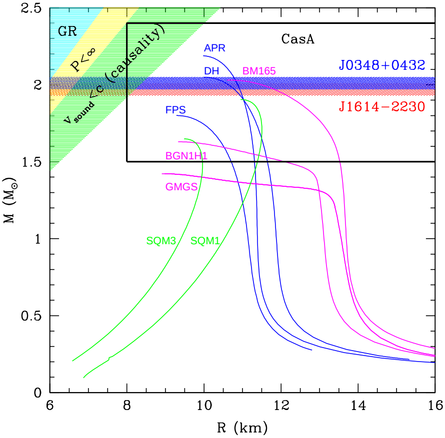
- Cottam et al., Nature (2002) : **narrow** absorption lines in the spectra of X-ray bursts with
$$z_g = 0.35.$$
- Lin et al., ApJ (2010) : lines do not come from the surface.

Mass-radius diagram



Astrophysical constraints: radius

Mass-radius diagram



Thermal emission of isolated NSs

Dependence of the fit on many parameters :

- chemical composition of the envelope,
- magnetic field *B*,
- distance to the source,
- …

→ not precise enough measurements : eg. CasA NS (Ho et al., Nature 2009).

Astrophysical constraints: radius

Quiescent thermal emission of accreting NSs

Low B and accreted atmosphere.
Determination of the radius observed at infinity :

$$R_{\infty} = \frac{R}{\sqrt{1-2GM/(Rc^2)}}$$

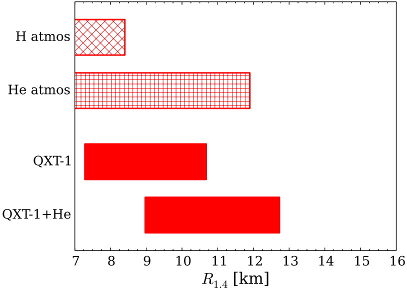
if the distance is accurately known eg. for NSs in globular clusters (GCs).

Results

- NGC 6397: H atmosphere vs. He atmosphere
  Heinke et al., MNRAS (2014)
- QXT-1: based on 6 objects, only H atmosphere
  Guillot & Rutledge, ApJ (2014)
- QXT-1+He: possibility of He atmosphere for NGC 6397
  Heinke et al., MNRAS (2014)

Limitations

- H or He atmosphere? He model gives R_{∞} $\sim$50% larger than H model.
- Large uncertainty in the interstellar absorption (N_{H} parameter).
- Lack for precise distance measurements. Athena and Gaia may help.



Astrophysical constraints: radius

Very powerful X-bursts from accreting NSs

= photospheric radius expansion bursts,

- strong enough to lift up the outer layers of the NS.

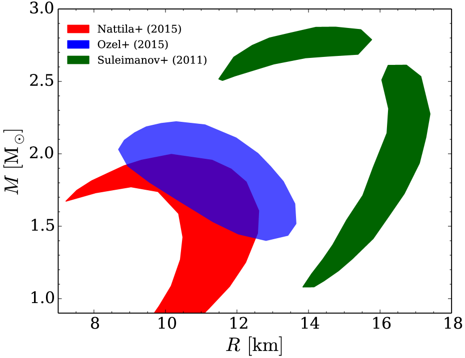
Limitations

eg. Özel et al. papers
Steiner et al., ApJ (2010)
Suleimanov et al., ApJ (2011)

- uncertainties in the modelling of the burst and the composition of the atmosphere.

4U 1724-307

- Suleimanov et al., ApJ (2011)
- Nättilä, Suleimanov et al. arXiv:1509.06561
- Özel et al. arXiv:1505.05155



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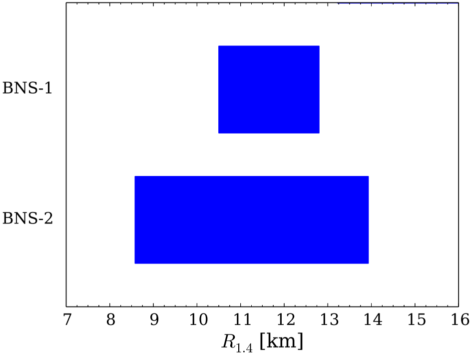
Results

- BNS-1: based on 3 objects
  Nättilä et al. arXiv:1509.06561
- BNS-2: based on 1 object
  Güver & Özel, ApJ (2013)



Astrophysical constraints: radius

Fitting the X-ray emission from radio millisecond pulsars

PSR J0437−4715

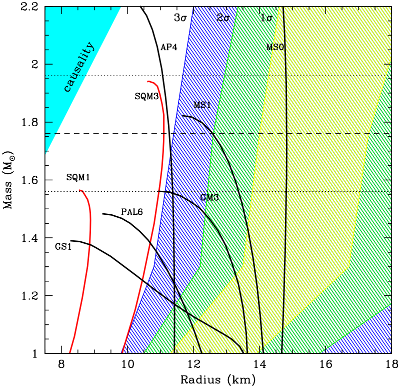
Bogdanov, ApJ (2013):

- Rotating NS with
- H atmosphere and
- two hot spots corresponding to the magnetic polar caps,
- fitting with the X-ray pulse profile.

\+ mass known from radio observations: $M = 1.76 \pm 0.2\ \mathrm{M}_\odot$.

→ $R > 12.29$ km (2σ)

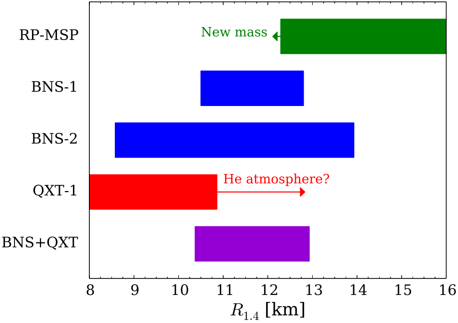
- new mass measurement from Freire et al. (unpublished): $M = 1.44 \pm 0.07\ \mathrm{M}_\odot$ → $R > 12.21$ km (2σ)



Astrophysical constraints: radius

Fitting the spectrum of

- X-ray emission from radio millisecond pulsars (RP-MSP);
- the quiescent thermal emission of accreting NSs (QXT);
- X-bursts from accreting NSs (BNS).



Based on most the recent publications. Adapted from Haensel et al. EPJA (2015)

- RP-MSP: Bodganov, ApJ (2013)
- BNS-1: Nättilä et al. arXiv:1509.06561
- BNS-2: Güver & Özel, ApJ (2013)
- QXT-1: Guillot & Rutledge, ApJ (2014)
- BNS+QXT: Steiner et al., ApJ (2013)

Conclusion

- inconsistency (see QXT-1 and RP-MSP),
- many remaining uncertainties in the modelling,
- inclusion of rotation: effect $\simeq$ 10%.
- future X-ray telescopes (NICER, Athena, LOFT?): $M-R$ constraints with a precision of $\sim$ 5%

Astrophysical constraints?

Radius15 conference

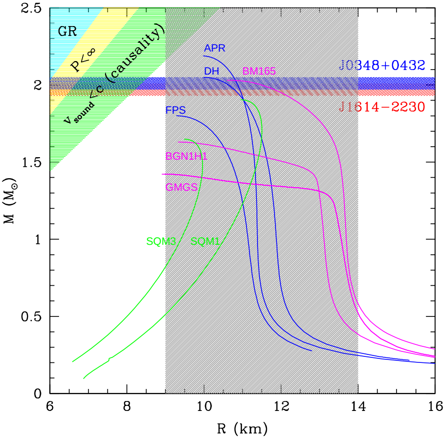
Montreal (CA), July 2015.
Consensus: $R = 9 - 14$ km
⇔ zero constraint!

Conclusion

No constraining measurements so far except the 2 $M_\odot$ NSs. But :

- More precise observations from the next generation of X-ray satellites;
- Other promising techniques eg. gravitational wave detection . . .

Mass-radius diagram



Thermal evolution of neutron stars

Cooling of isolated NSs

$t = 0$

- $T \sim 10^9 - 10^{10}$ K.

$t \sim 1$ year

- the core cools by ν-emission,
- the crust by heat diffusion.

$\rightarrow$ crust properties.

$t \lesssim 10^5$ years

- thermal balance between the core and the crust,
- cooling by ν-emission;

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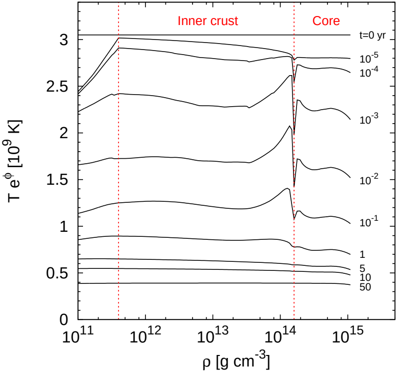
$t \gtrsim 10^5$ years

- cooling via emission of photons from the surface.

Evolution of the temperature profile



Non-superfluid 1.4 $M_\odot$ NS model.

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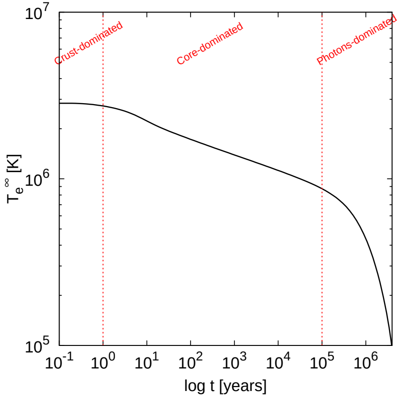
Evolution of the surface temperature



Non-superfluid 1.4 $M_\odot$ NS model.

Observations of isolated NSs

X-ray telescopes eg. XMM-Newton, Chandra, AstroH, NuStar, Athena, . . .

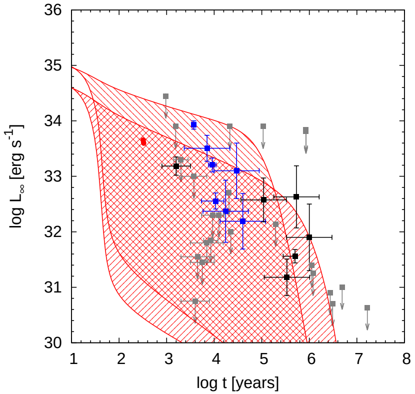
Biases

- small objects: detection of NSs with $T \sim 10^5 - 10^7$ K within few kpc
- middle-aged NSs with extended supernova remnant.

Age and temperature determination

- age: uncertain unless the supernova as been observed in the past (cf. Crab pulsar): estimation from spin-down or modelling the expansion of the supernova remnant.
- temperature: composition of the envelope unknown: H, He, Fe ?

Observational data



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Constraints?

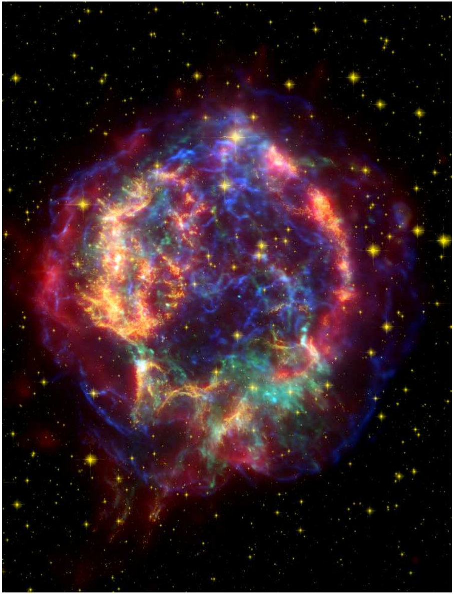
Too many uncertainties:

- the mass
- the atmosphere composition
- the age
- the distance
- ...

to have constraints.

Plus dramatic effect of the magnetic field (see eg. Viganó et al. MNRAS 2013) → modeling of the magneto-thermal evolution.

Cooling of an isolated NS?



Cassiopeia A neutron star

- one of the youngest-known SN remnants in the Milky Way,
- SN most probably observed by John Flamsteed in 1680 (agreement with the expansion of the remnant),
- age = 330 ± 20 yr,
- distance d = $3.4^{+0.3}_{-0.1}$ kpc.

Ho & Heinke, Nature (2009) :

the compact object is a neutron star with a carbon atmosphere.
→ First determination of the atmosphere composition of an isolated NS.

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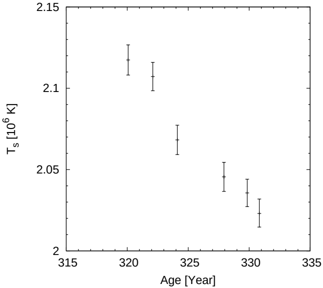
Analysis of 10 years of X-ray observations :



Data from Shternin et al., MNRAS (2011).

→ First direct observation of the cooling of an isolated NS.

Cassiopeia A neutron star

Shternin et al., MNRAS (2011) & Page et al., PRL (2011)

Two ingredients :

- recent triggering of the PBF process due to neutron ${}^3P_2$ superfluidity : $T_{\rm C} \sim 5 - 9 \times 10^8$ K,
- the protons are already superfluid (in the ${}^1S_0$ channel) : $T_{\rm C} \sim 10^9$ K.

→ first direct evidence for superfluidity in the core of neutron stars.

Posselt et al., ApJ (2013)

- re-analysis of two observations with their own model of C atmosphere and taking into account instrumental effects;

→ NO temperature decline at all . . .

Modeling of the observations :

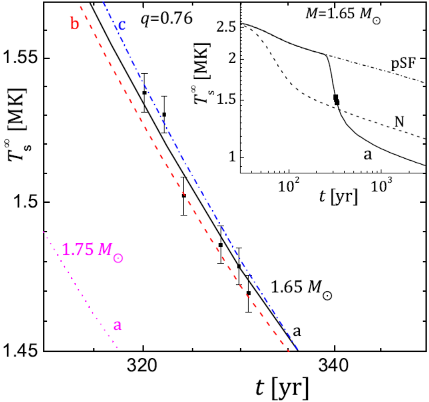
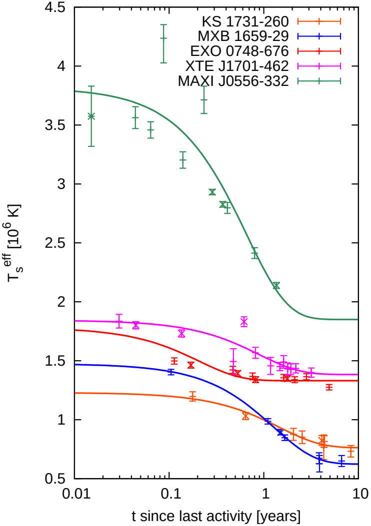


Figure : Cooling curves of a 1.65 $M_\odot$ star for different superfluid properties in the core. From Shternin et al., MNRAS (2011)

Thermal evolution of accreting NSs

Thermal relaxation

= after end of accretion



Quasi-Persistent X-Ray Transients

Two phases:

- accretion during ∼ years to decades,
- quiescence when accretion stops.

Deep crustal heating scenario

While the accreted matter sinks into the crust, it undergoes a series of reactions that heats the crust.

KS & MXB

Shternin et al., MNRAS (2007); Brown & Cumming, ApJ (2009) :

- exclude a very efficient ν-process (dURCA) in the core,
- crystalline crust with superfluid neutrons.

Thermal evolution of accreting NSs

Thermal relaxation

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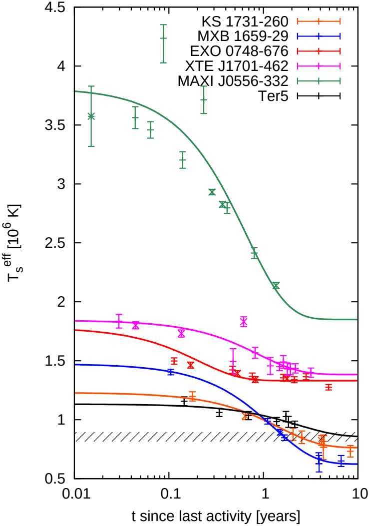


New type of source: normal transient

IGR J17480-2446 in Terzan 5 (Degenaar et al., ApJ 2013):
accreted during ∼ 10 weeks only.

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	165 ± 60
XTE	95 ± 15
MAXI	240 ± 60
Ter 5	100 ± 10

Constraints

on the crust properties:

- composition,
- nuclear reactions due to accretion,
- neutron superfluidity.

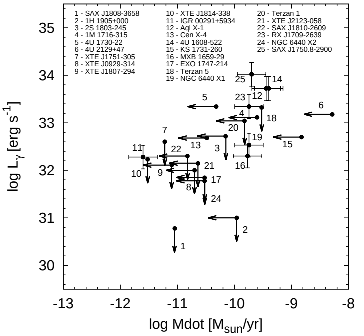
Thermal evolution of accreting NSs

Soft X-ray Transients

NSs in close binaries with a low-mass companion undergoing:

- repeated short periods of accretion;
- long quiescent phases.

Observations



Luminosity in quiescent state

Assuming a quasi-stationary evolution:

Luminosity of photons emitted at the surface L_γ

$=$ power from the heat generated in the interior by nuclear reactions $(\langle \dot{M} \rangle)$

$-$ luminosity of neutrinos emitted from the whole interior L_ν.

Uncertainties

- observations for at most several decades:
  $\langle \dot{M} \rangle$ estimated but large uncertainties;
- uncertainty on the distance.

Thermal evolution of accreting NSs

Soft X-ray Transients

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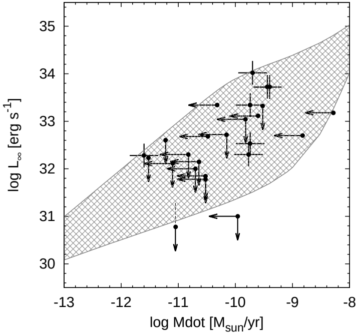
Modelling



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Ingredients

Properties of the core:

- EoS,
- baryon superfluidity.

Thermal evolution of accreting NSs

Soft X-ray Transients

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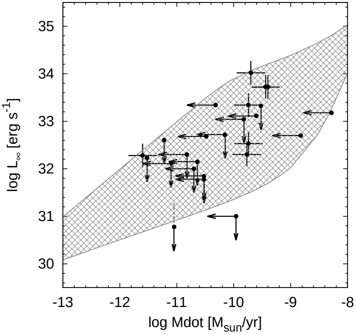
Modelling



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Constraints

Low quiescent luminosity:

→ very high ν losses ie. large L_ν;

- the most efficient process: dURCA is necessary:
  $B_1 \rightarrow B_2 + l + \bar{\nu}_l$
  Conservation of momentum → density threshold.

Not all EoS allow for the dURCA.

Conclusion

NSs are at the interface between astrophysics and nuclear physics

- Goal: constrain the properties of the nuclear force with astrophysical observations and *vice-versa*.

- Currently: only constraints from mass measurements;
- Hopefully more to come in the next few years thanks to new X-ray telescopes.

- constraints on the EoS from modeling of the thermal evolution of NSs?
  - isolated NSs: too many uncertainties except if the cooling of a single source is monitored,
  - thermal relaxation of QPXRTs: constraints on the properties of the crust,
  - quiescent states of SXTs: constraints on the core properties.

QCD phase-diagram