Connections between the Different Neutron Star Classes

R. Turolla
Dept. of Physics and Astronomy,
University of Padova, Italy

The NS Bestiary

- Radio-pulsars (PSRs)
- Anomalous X-ray pulsars (AXPs), soft gamma-repeaters (SGRs)
- Central compact objects (CCOs)
- Thermally-emitting NSs (XDINSs/INSs)
- Rotating radio transients (RRaTs)


The Aberdeen Bestiary (12th century)

NSs in binaries (LMXBs, HMXBs)

"The beauty of the universe consists not only of unity in variety, but also of variety in unity."
U. Eco, *The name of the rose*

What (likely) Makes NSs Different ?

- The way they are born
  - Mass (and Radius, M, R → EOS !)
  - Initial spin period (P_0)
  - Initial magnetic field (B_0, strength and topology both internal and external)
- Age
  - Evolution of B, P, temperature, …
- Interaction with ambient medium (SNR ejecta, fallback, …)

What Do We Measure ?

- Surface temperature from spectral fitting
- P and $\dot{P}$ from timing
- B_p and age from magneto-rotational braking

$$B_p = 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G},$$

$$\tau = P/2\dot{P}\,,$$

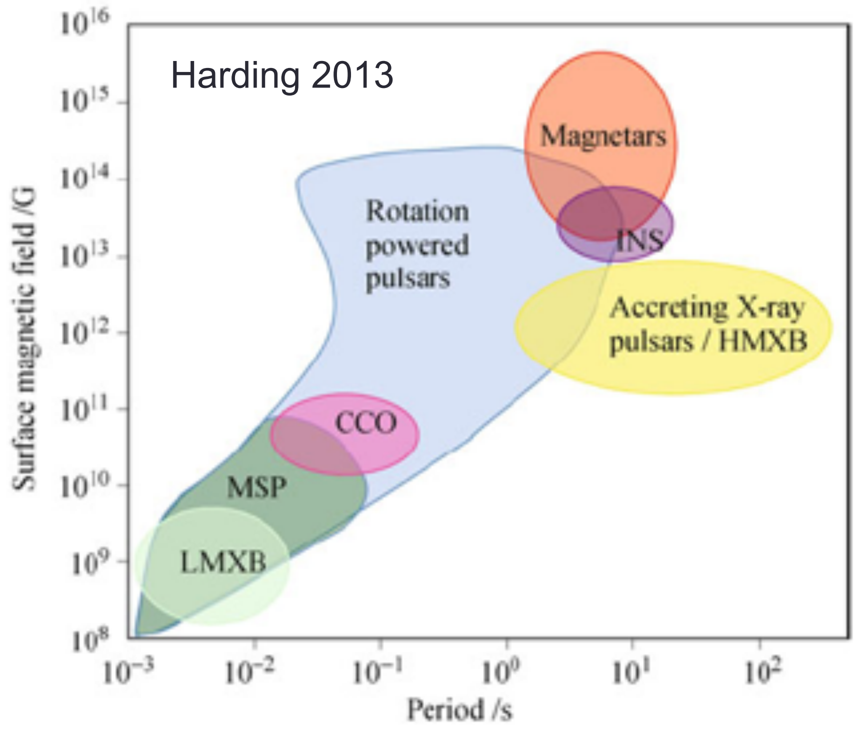
$$\dot{E} = 3.9 \times 10^{46}\, P/\dot{P}^3\ \mathrm{erg/s}$$

Hold if B is a constant dipole and $P_0 << P$!

- M nearly impossible in INSs; R from thermal emission, but...; M/R from GR (red-shifted lines, pulse profile shape → LOFT)

The Powerhouse

- Rotation ($\dot{E} > L_{bol}$, RPPs)
  - PSRs, RRaTs
- Residual heat
  - XDINSs, CCOs
- Magnetic energy
  - SGRs, AXPs
- Accretion
  - HMXBs, LMXBs



Thermally-emitting INSs (XDINSs) - I

- Soft X-ray sources, seven known (hence the nickname "Magnificent Seven", or M7)
- Faint optical counterparts ($m_v > 25$)
- Close-by, $D \approx 150$-500 pc
- Slow rotators, $P \sim 3$-11 s, $\dot{P} \approx 10^{-13}$ s/s
  - $B_p \sim 1.5$-3.5×10^{13} G, $\tau \sim$ a few Myr, $\tau_{kin} \sim 5$-10 times shorter
- Radio-silent
  - Intrinsically radio-quiet ? Misaligned PSRs ? (Kondratiev et al. 2009)

Thermally-emitting INSs (XDINSs) - II

- Thermal spectrum, T ~ 50-100 eV, R_{BB} ~ 5-10 km
- Broad absorption features @ 300-700 eV
  - Proton cyclotron/Atomic transitions ? (Turolla 2009, Kaplan & Van Kerkwijk 2011)
- Steady, long-term spectral changes in RX J0720
  - Precession (Haberl et al 2006) ? Glitch (Van Kerkwijk et al. 2007, Hohle et al. 2012) ?

Magnetar Candidates (SGRs/AXPs) - I

- About 20 known
- Short (0.1-1 s), energetic (10^{39}-10^{41} erg/s) bursts and giant flares (up to 10^{47} erg/s)
- Variable (transient) persistent emission ($L_X \approx 10^{32}$-10^{36} erg/s)
- Thermal + power-law tail spectrum (PL extends up to 200 keV), T ~ 0.5 keV, $R_{BB} < 1$ km
- P ~ 2-12 s, huge $\dot{P} \approx 10^{-10}$-10^{-13} s/s
- $B_p \approx 10^{13}$ -10^{15} G, $\tau \approx$ 1-10 kyr, $L_X >> \dot{E}$

Magnetar Candidates (SGRs/AXPs) - II

- Three "low-field" magnetars recently discovered (Rea et al. 2010, 2012, 2013)
  - $B_p \leq 10^{13}$ G, $\tau \approx 1$ -10 Myr,
  - Ultra-strong, local field measured in SGR 0418 ($\sim 10^{15}$ G, Tiengo et al. 2013)
- Magnetar-like activity detected in two RPPs (Gavriil et al. 2008, Levin et al. 2010)

Radio Pulsars (including HBPSRs)

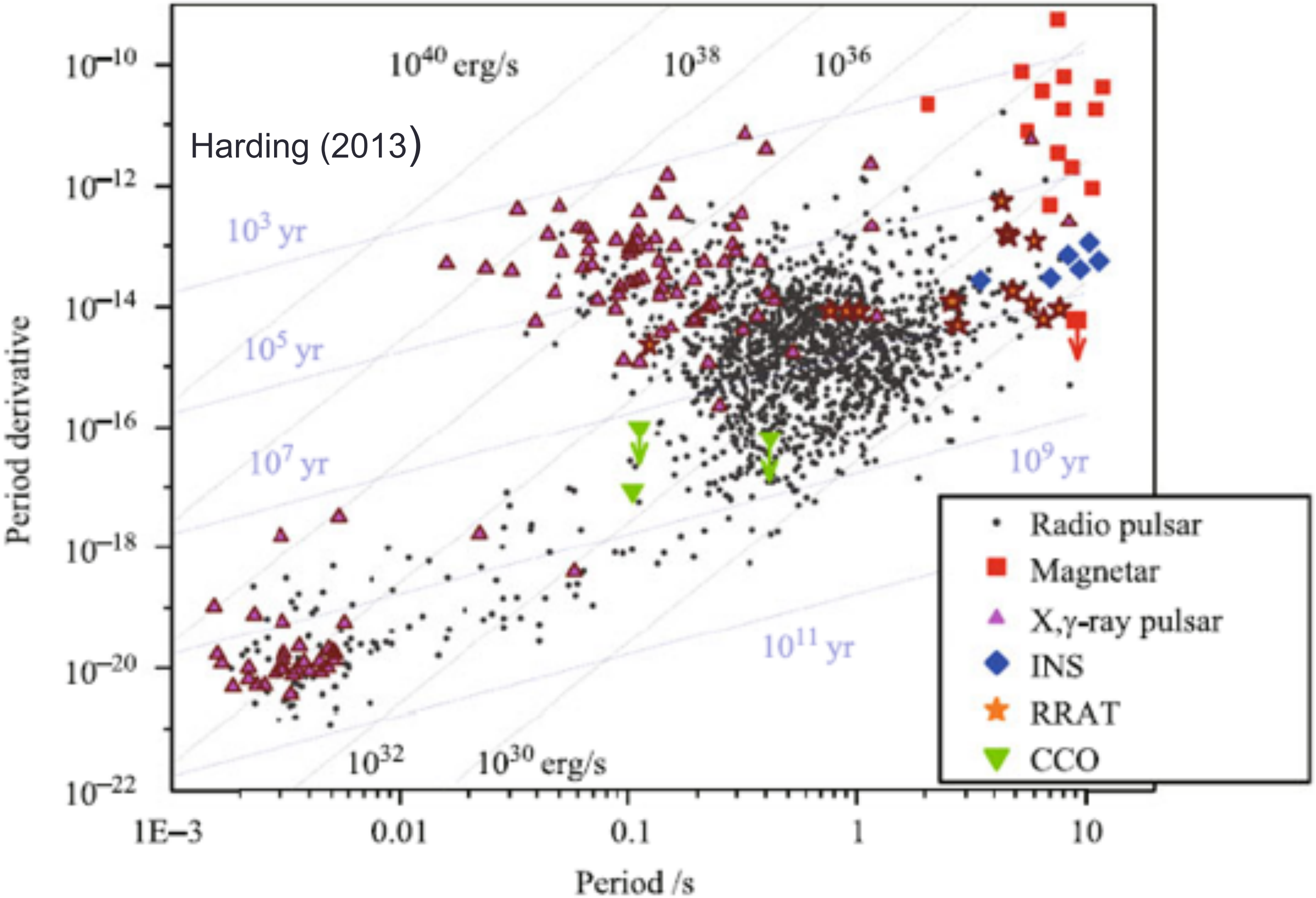
- More than 2000 discovered in the radio, ~ 100 in the X-rays
- Wide range of P (≈ 1ms-10 s) and B_p (≈ 10^8-10^{14} G)
- X-ray emission
  - Thermal (~ 0.1 keV), from
    - hot spots (MSPs, relatively old PSRs)
    - the entire cooling surface (relatively young PSRs)
  - Non-thermal, from the magnetosphere
- High-B PSRs are “normal” RPPs with a field in the magnetar range (~ 20 with B_p > 5×10^{13} G) but no detected magnetar-like activity

Rotating Radio Transients (RRaTs)

- About 80 known, “normal” radio pulsars with an exceedingly high nulling fraction (> 99%, Burke-Spolaor 2013), i.e. they emit sporadic, single radio pulses (McLaughlin et al. 2006)
- $P \sim 0.5$-7 s, $B \sim 10^{12}$-10^{14} G, $\tau \sim 0.1$-3 Myr
- PSR J1819-1458 ($P = 4.3$ s, $B = 5\mathrm{x}10^{13}$ G) detected in X-rays (McLaughlin et al. 2007, Miller et al. 2013)
  - Thermal spectrum ($T \sim 140$ eV, $R_{BB} \sim 8$ km)
  - One (two ?) absorption feature @ ~ 1 keV
  - $L_X > \dot{E}$ (?)
  - Bright PWN (Rea et al. 2009)

Central Compact Objects (CCOs)

- INS X-ray sources at the centre of SNRs, 8 found
- Young (SNR age $\tau_{SNR} < 10^4$ yr)
- Radio-silent, no counterpart at other wavelengths
- Steady, thermal spectrum, quite large pulsed fraction, absorption lines in some sources
- P and $\dot{P}$ measured (or constrained) in 3 sources (Pup A, Kes 79, 1E 1207; Gotthelf 2010, Halpern & Gotthelf 2010, 2011)
    - P ~ 0.1 -0.4 s
    - $B \approx 3\text{-}10 \times 10^{10}$ G, the “anti-magnetars”
    - $L_X > \dot{E}$, $\tau >> \tau_{SNR}$


Harding (2013)
10^{40} erg/s
10^{38}
10^{36}
10^{3} yr
10^{5} yr
10^{7} yr
10^{9} yr
10^{11} yr
10^{32}
10^{30} erg/s
Period derivative
Period /s
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
1E−3
0.01
0.1
1
10
Radio pulsar
Magnetar
X,γ-ray pulsar
INS
RRAT
CCO

The Role of the B-Field

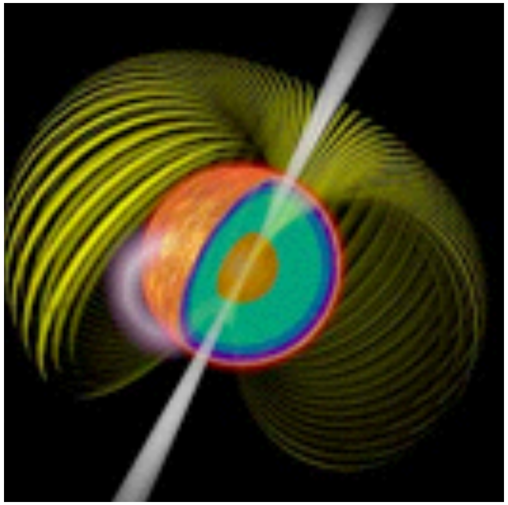
- Isolated NSs span a much wider range in B than PSRs, from 10^{10} G to 10^{15} G
- Strength does not matter !
- There are NSs with high B that do not behave like magnetars (HBPSRs, XDINSs) and NSs with low-enough B that do !

$B > B_Q$

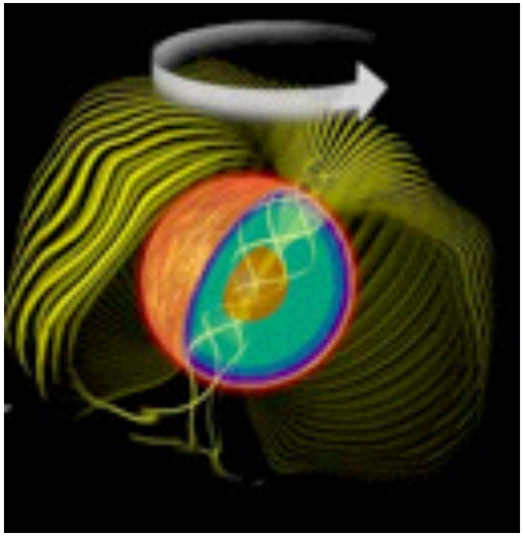
A Magnetar at Work

- What really matters is the internal toroidal field B_φ
- A large B_φ induces a rotation of the surface layers
- Deformation of the crust ⟹ fractures ⟹

  bursts/twist of the external field

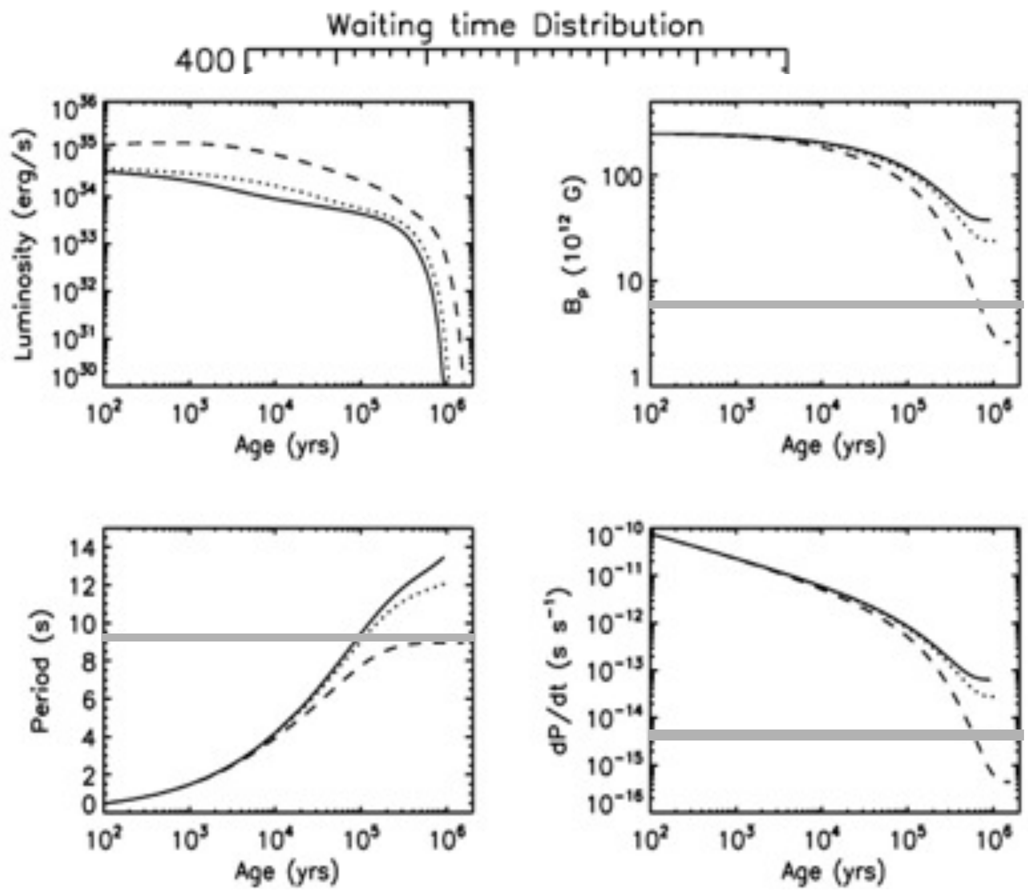


High-B PS



SGR/AXI

Evolution of the B-field



SGR 0418 (Turolla et al. 2011)

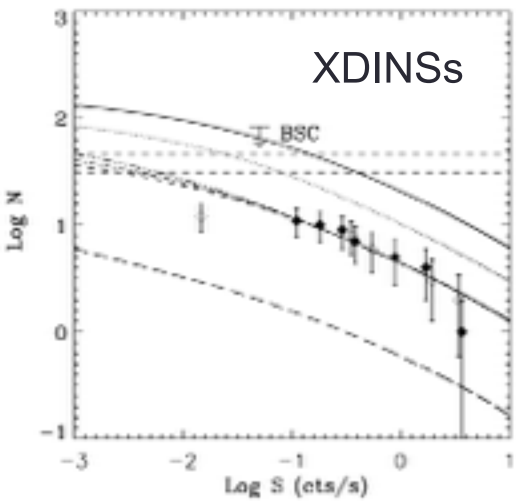
Getting to GUNS ? - I

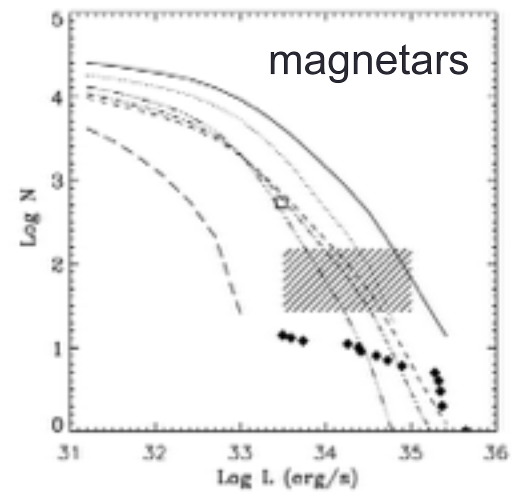
Grand Unification (of) Neutron Stars !

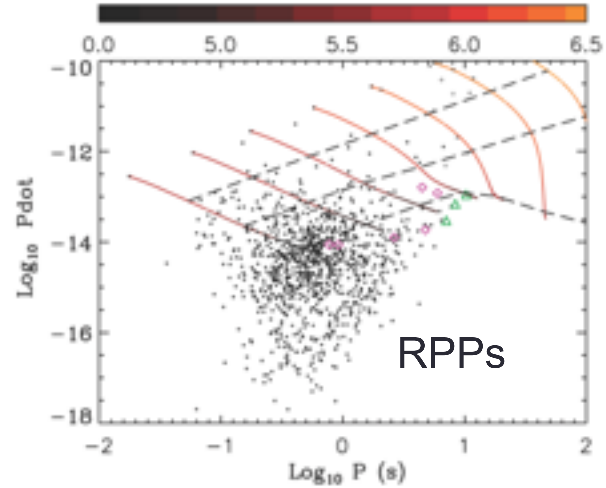
- Present knowledge of SN explosion mechanism insufficient to predict initial NS parameters
- Use different approaches (population synthesis, cooling curves, P-Ṗ diagram) to confront (magneto-thermal) NS evolutionary models with observations
- Pinpoint key initial parameters and check possible evolutionary links among NS classes

Getting to GUNS ? - II

- (Separate) population synthesis calculations of RPPs, XDINSs and SGRs/AXPs, including magneto-thermal evolution (Ohmic decay only, crustal poloidal+toroidal field; Popov et al. 2010)
- The collective properties of the three classes are recovered assuming that B_0 has a log-normal distribution ($\langle \log B_0 \rangle \sim 13\text{-}13.5$)

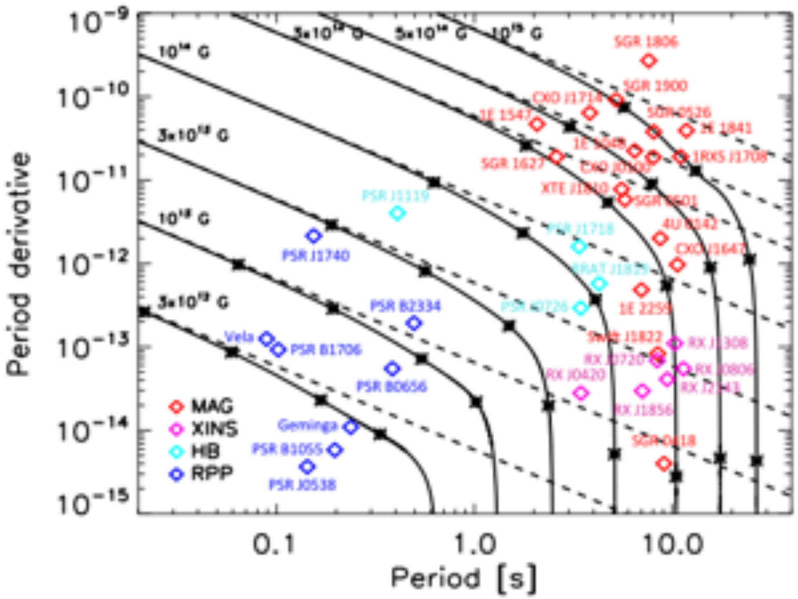


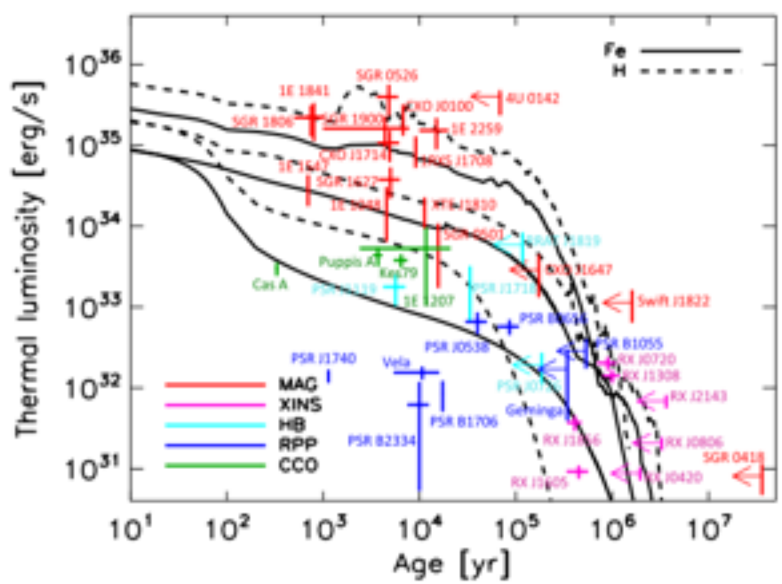




Getting to GUNS - III

- Only recently Hall drift included in magneto-thermal codes (Viganò et al. 2012, 2013)





Crustal field, M=1.4$M_\odot$, B_0 poloidal (Viganò et al. 2013)

Variety in unity, or the NSs Jigsaw

B	10	B
RPPs, HBPSRs ↓ ***Little evolution***	***Moderate magnetars*** ↓ ***"low-field" magnetars, XDINSs, RRaTs***	Extreme magnetars ↓ ?

RRATs

H

CCOs

The CCOs Plight

- Anti-magnetars, B_p £ 10^{11} G
- Since they are young ($\tau_{SNR} < 10^4$ yr), $P \sim P_0$
- Are they born with such low fields ?
  - Very few of them
  - B_p £ 10^{11} G too low to produce surface temperature variations and hence pulsations
- Born with standard field buried after fallback (Gotthelf et al. 2010, Shabaltas & Lai 2012, Viganò & Pons 2012)
  - Subsurface field can produce temperature anisotropy
  - The buried field can re-emerge at later times moving CCOs out of the underpopulated region of the P-$\dot{P}$ plane

Is All Well ?

- Promising steps towards GUNS: key role of B and of its evolution
- Several key issues still open
  - Better characterization of the quiescent state of transient magnetars and of HBPSRs X-ray properties to further validate magneto-thermal evolution models
  - What are the absorption features seen in XDINSs and RRaTS ? Are XDINSs extreme RRaTs ?
  - Ephemeral, peculiar radio emission observed from outbursting magnetars and from a 4.3 s HBPSR (Levin et al. 2010). What is producing this (Rea et al. 2012) ?
  - Where are the descendants of CCOs ? Is Calvera an orphan CCO (Zane et al. 2010) ?

Overview

- Are INSs thermal emitters ?
- Importance of thermal emission
- Observations of INSs
- The state of the NS surface
    - Gaseous
    - Liquid/solid
- Emission from NS atmospheres
    - Non-magnetic/magnetic models
    - Different chemical compositions
- Emission from “bare” NSs

INS Observations

- Thermal radiation from a NS first detected by EXOSAT and Einstein
- Many more sources found by ROSAT, Chandra and XMM-Newton
- At present about 80 ??? sources known: PSRs, AXPs and SGRs (the magnetar candidates), CCOs, RRaTs, XDINSs, Geminga and Geminga-like objects
- “Isolated” NSs in binaries: SXRTs