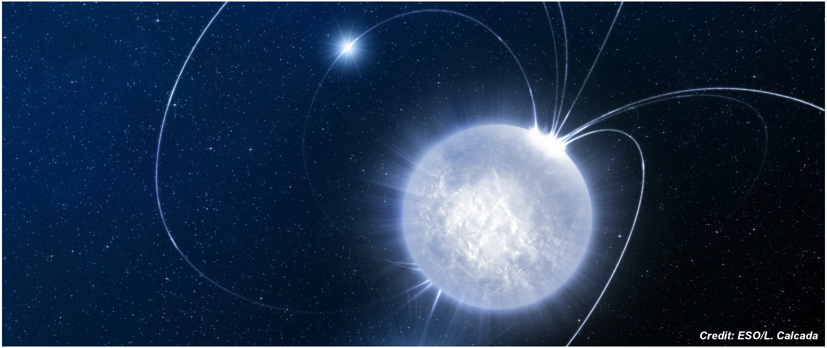

The most "magnificent" of the seven?

A candidate spin and spin-down for RX J1605.3+3249

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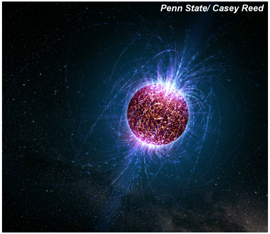
The bulk of the neutron star population

Two main groups, discovered from radio surveys:

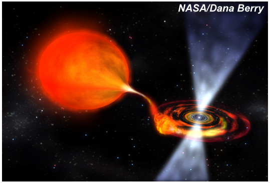
Standard (rotation-powered) pulsars

- young objects emit accross the entire electromagnetic spectrum
- slow down due to magnetic dipole radiation and particle acceleration
- $P \sim$ 0.1–1 s; $B \sim 10^{12}$ G

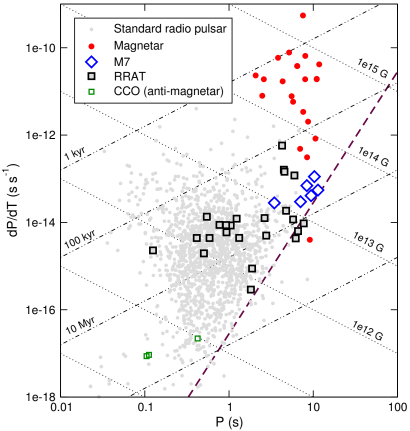


Millisecond (recycled) pulsars

- fast spin and low magnetic fields
- high energy (X-rays, γ-rays) and radio
- old neutron stars “recycled” by accretion in a binary system



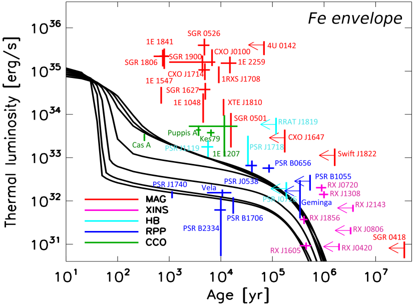
Peculiar groups of neutron stars

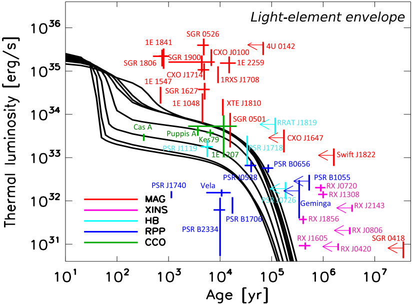


1. magnetars show complex phenomenology, dominated by manifestations of a super strong magnetic field
2. xdins *aka* the “M7” rotate more slowly and have higher thermal luminosity than standard pulsars of similar age
3. ccos are young INSs, with no magnetospheric emission and very low spin down
4. rrats show transient bursts of radio emission and have properties that vary widely

Are we observing different “species”, or the same “animal at different ages or in a different social environment” ? (J. Pons, F&F 2013)

Standard cooling *vs.* observations





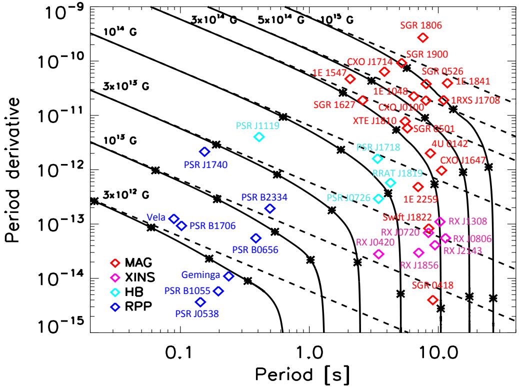
(Viganò et al. 2013)

- most rotation-powered pulsars agree with theory
- CCOs are consistent with light-envelope models
- magnetars and the M7: too bright (hot) for standard cooling

Correlation between B and kT: additional heating of the neutron star crust at work by means of magnetic field decay (Heyl, Aguilera, Pons et al.)

What happens when a magnetar ages?

- Viganò, Rea, Pons et al.: 2d simulations to track the coupled $B - kT$ evolution in neutron stars for the first time



(Viganò et al. 2013)

1. torque brakes spin to asymptotic value
2. field dissipates heating the crust

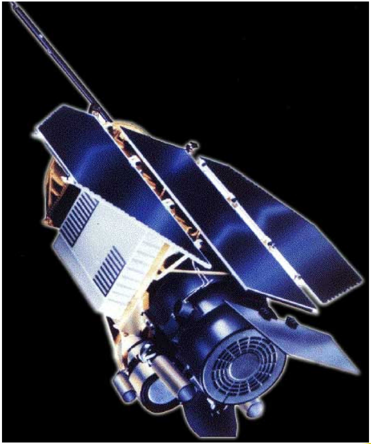
The neutron star is hotter than ordinary pulsars of similar ages

The M7 could be the direct descendents of magnetars

The “Magnificent Seven”

RASS: discovery of 7 X-ray bright INSs sharing similar properties

- nearby ($d \lesssim 1$ kpc)
- radio-quiet
- soft, purely thermal X-ray emission
- luminosity in excess of spin-down power
- cooling, middle-aged objects
  (proper motion studies)
- long spin periods ($P \sim 3$–10 s)
- high magnetic fields (10^{13}–10^{14} G)
- absorption lines at low energies



RX J1605.3+3249 (*aka* RBS 1556)

The third brightest amidst the M7; the only one still lacking a detected periodicity

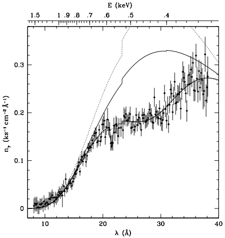
Proper motion and (likely) birthplace constrains its age ∼0.5–3.5 Myr

(Motch 2005, Tetzlaff et al. 2012)

Observed ten times with XMM (2002–2006)

Broad absorption feature in the spectrum at 0.45 keV

(van Kerkwijk et al. 2004)

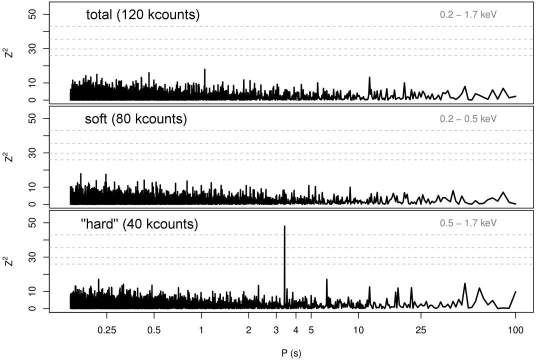


Upper limit $p_{\rm f} < 5\%$ (pn timing mode)

2006: bad weather, 80% reduced time

New XMM observation after a hiatus of 6 yr (visibility constraints):
60 ks EPIC imaging FF mode (F. Haberl, PI)

Unveiling the neutron star spin period



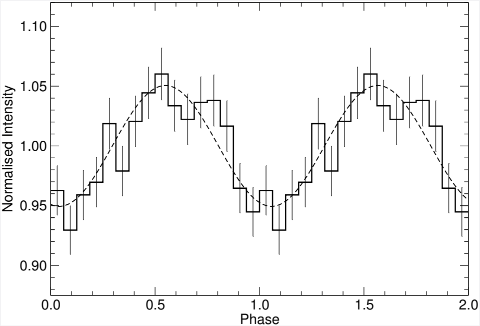
Z^2_n (Rayleigh) tests

- Blind searches:
  - EPIC ($P >$ 5.2 s)
  - pn ($P >$ 0.15 s)
- Steps of 2 μHz
- Tested different:
  - energy bands
  - extraction regions
  - photon patterns

- Periodic signal $\nu \sim$ 0.2952 Hz revealed when soft photons are discarded
- Only ~30% of all source events show a significant modulation
- Detection at 4 σ c.l. ($\nu =$0.01–6.81 Hz; $\gtrsim 10^5$ independent trials)

Energy-dependent pulsed fraction

Folded pn light curve at $P = 3.39\,\mathrm{s}$



Maximum $p_f = 5.1(7)\%$ (0.5–1.7 keV)

No higher harmonics; sinusoidal pulse profile

Most of the source photons show low-amplitude modulation ($p_\mathrm{f} < 3\%$, 3σ)

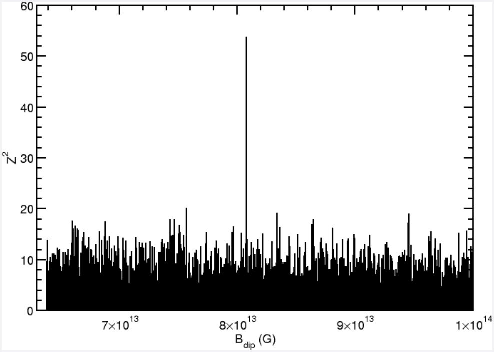
Unpulsed soft photons smear out the significance of the signal detected at harder energies

Other INSs: increasing p_f with energy (RX J1856); changes in pulse profile (RX J1308); phase-dependent spectral variations (RX J0720)

Estimating the pulsar spin-down rate

Joined 2-d $Z_n^2(\nu, \dot{\nu})$ search

- pn observations:
  - 2012 (FF; 60 ks)
  - 2003 (LW; 40 ks)
  - 2002 (TI; 3×33 ks)
- Coherent combination of photons TOAs
  $\phi_j = \nu(t_j - t_0) + \dot{\nu}\frac{(t_j - t_0)^2}{2}$
- Reasonable range of $\nu, \dot{\nu}$
- $\gtrsim 10^8$ independent trials
- Z^2 power consistent with ∼4% modulation



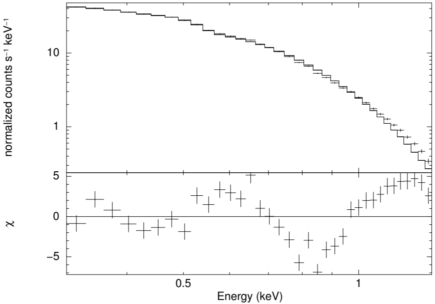
Candidate for the pulsar spin down
$\dot{\nu} \sim -1.6 \times 10^{-13}$ Hz s^{-1} (2σ–3σ c.l.)

Solution implies a magnetic field of $B_{\rm dip} \sim (7.4 - 8) \times 10^{13}$ G
All other possible $(\nu, \dot{\nu})$ combinations below the 1-σ c.l.

Spectral energy distribution

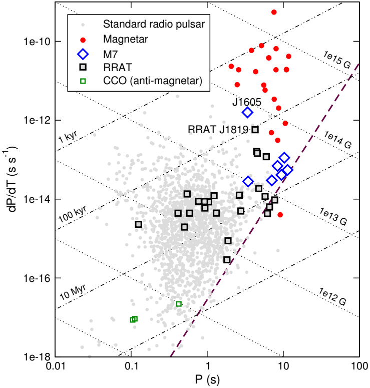
- Analysis: AO11 data + archival (14 pn/MOS spectra, $> 4 \times 10^5$ counts)

1. main blackbody ($kT_{\rm hot} \sim$ 100–110 eV)
2. additional cool BB ($kT_{\rm cool} \sim$ 45–60 eV)
3. two absorption features ($\epsilon_2 \sim 2\epsilon_1$)
4. non-thermal tails constrained below 0.3% of the source flux (3σ)



- Size of emission regions: $R_{\rm cool} \sim$ 11 km and $R_{\rm hot} \sim$ 3 km ($d \sim$ 350 pc)
- RGS spectrum confirms narrow absorption feature at 0.57 keV (Hohle 2012)
- No significant long-term variability in the source properties

As close to a magnetar as a M7 can get?



- The M7, up to now: homogeneous class of cooling neutron stars
- Range of kT, L_X, P, $\dot{P}$, age accounted by evolutionary models with B-decay ($B_0 \sim (3-5) \times 10^{14}$ G; Viganò et al. 2013)
- Our results suggest that J1605 could be the INS with highest $B_{\rm dip}$ amidst the M7
- Similar to the only RRAT so far detected in X-rays, J1819-1458
- J1819-1458 could also have evolved from a magnetar (Lyne et al. 2009)

High $B_{\rm cyc} \sim 8 \times 10^{13}$ G also derived from the line energy detected at 0.4 keV (assuming p-cyclotron absorption)

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Perspectives

1. Determine a precise timing solution
   - *obtain an accurate measurement of $\dot{P}$ (hence $B_{\rm dip}$)*
2. Perform phase-resolved spectroscopy
   - *constrain the geometry of the emitting regions*
3. Confirm the high inferred magnetic field
   - *vacuum polarization can leave imprints in the spectrum and light curves (Perna et al. 2012)*
   - *high-B neutron stars dominated by thermal emission are obvious targets*
4. Investigation of co-added RGS data to better characterise narrow absorption lines

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Summary

1. The “Magnificent Seven”: homogeneous group of cooling INSs, could be the descendants of magnetars
   - J1605: the only source still lacking a detected periodicity
2. XMM: detection of pulsed emission (energy-dependent p_f)
   - candidate P within the narrow range observed in the M7
   - “hard” pulsed spectrum (>0.5 keV), unpulsed with $p_f < 3\%$
3. Archival observations: constraints on the spin-down rate
   - inferred $B_{\rm dip}$: the highest among the seven sources?
4. SED: kT anisotropy and absorption lines (harmonically related?)
5. Next: precise timing solution, phase-resolved spectroscopy

Thank you!