First dedicated observations of the isolated neutron star in the Carina Nebula

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PHYSICS OF NEUTRON STARS

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Outline

1. Scientific case
   - Peculiar groups of isolated neutron stars
2. XMM J1046: a new M7?
   - Archival X-ray observations
   - AO9 observations: goals and expectations
3. Results
   - Timing analysis
   - Spectral analysis
4. Summary and outlook

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"Peculiar" isolated neutron stars

Discoveries in X-rays/radio (over the last decade):
peculiar INSs that changed the standard picture of pulsar evolution

- XDINS a.k.a. "The Magnificent Seven"
- Rotating radio transients (RRATs)
- Magnetar candidates: AXPs and SGRs
- Central compact objects in SNRs (CCOs)

Still very few compared to the main radio pulsar population but very important:

1. investigation of individual sources: physics at extreme g, B
2. relations between groups: neutron star phenomenology
3. finding missing links: comprehensive picture can be aimed for

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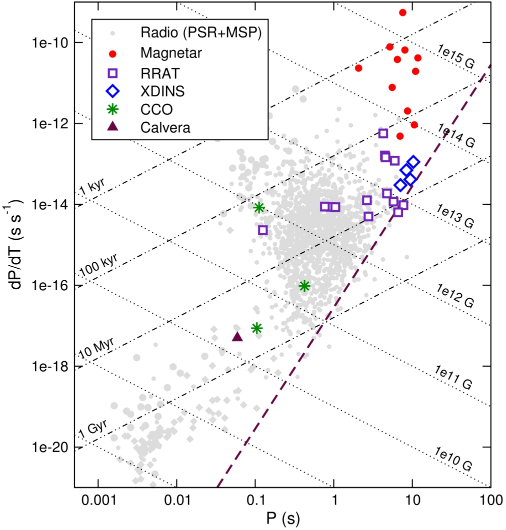
The M7: what's peculiar about them?



Radio pulsars:

- $P = 0.1 - 1$ s
- $B \sim 10^{12}$ G

When detected at high energies:

- young objects: dominated by magnetospheric activity
- middle-aged / old pulsars may show: cooling surface, hot polar caps, remnant magnetospheric emission
- $L_X \ll \dot{E}$ (spin-down)

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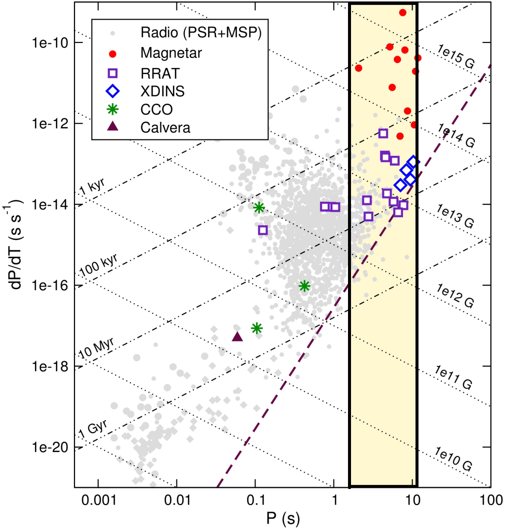
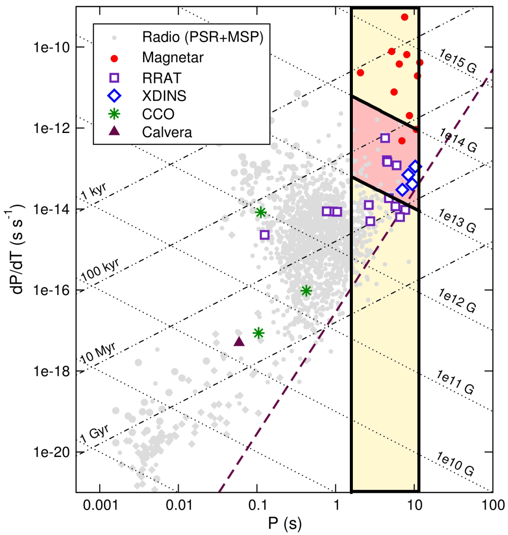


XDINS:

- local group
  - $N_{\mathrm{H}} \sim$ few $10^{20}\,\mathrm{cm}^{-2}$
  - $d < 1\,\mathrm{kpc}$
- cooling, $kT \sim 40 - 100\,\mathrm{eV}$
- middle-aged, $10^5 - 10^6$ yr
- radio-quiet

Relative to radio PSRs they rotate slower ($P \sim 3 - 10\,\mathrm{s}$)...

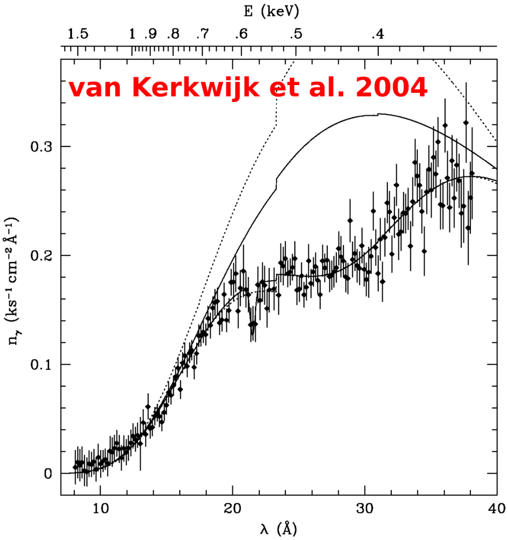
The M7: what's peculiar about them?



. . . and have higher inferred magnetic fields ($B \sim 10^{13} - 10^{14}$ G)

(somewhat intermediate between normal radio pulsars and magnetars)

The M7: what's peculiar about them?



- spectra purely thermal, very soft, low absorbed
- BB-like, usually with broad absorption features
- $L_X \gtrsim \dot{E}$; no X-ray hard (non-thermal) component
- constant X-ray flux and spectral properties (usually)

Why so many similar INSs in the solar vicinity? How numerous are they in the Galaxy?

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XMM J1046: a younger and more distant XDINS?

Detected in many occasions in the last ten years by XMM-Newton and Chandra (Pires et al. 2009)

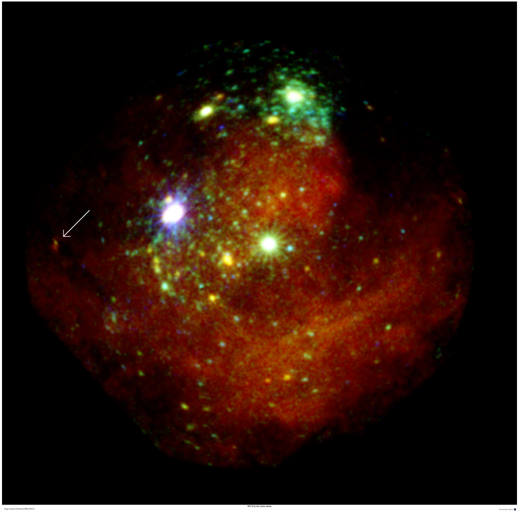

Image courtesy of Rosemary Willatt (ESAC) and ESA

- FOV of η Car
- soft BB; constant flux
- $kT = 117 \pm 14\,\mathrm{eV}$
- $N_\mathrm{H} = (3.5 \pm 1.1) \times 10^{21}\,\mathrm{cm}^{-2}$
- no counterparts (radio, $m_V > 27$, new VLT limit)
- no pulsations $p_f > 30\%$ (3σ, $P = 0.15 - 100\,\mathrm{s}$)
- possibly younger and closer to birthplace than the M7

Problems:

- large off-axis angles $\theta \sim 9'$
- short $t_\mathrm{exp} \lesssim 15\,\mathrm{ks}$
- near/in CCD gap

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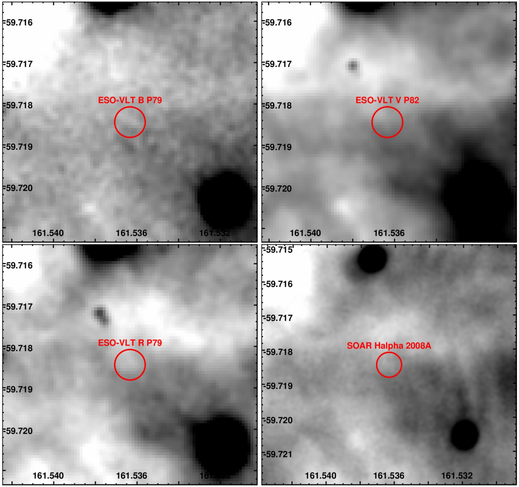

Upper limits on the optical counterpart

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First dedicated X-ray observations of XMM J1046

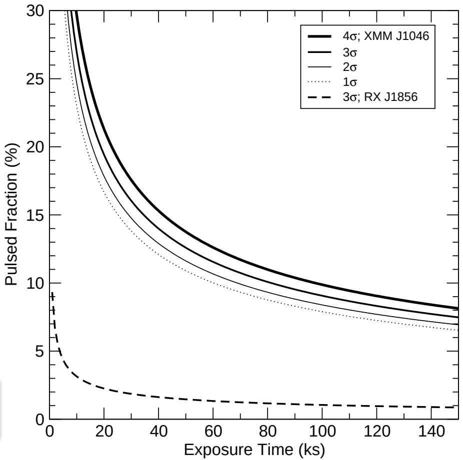
Immediate goals:

1. Determine the spin period
2. Better spectral energy distribution
3. Estimate *B* from absorption lines

Configuration and expectations:

- 90 ks with EPIC in small window (SW) mode and thin filter
- $p_f \gtrsim 15\%$, $E \gtrsim 0.5\,\mathrm{keV}$ (conservative)

Sensitivity to detect pulsations strongly dependent on source brightness



Results: timing analysis

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Results: timing analysis

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2. No pulsations in the $P = 0.6 - 10000\,\mathrm{s}$ (EPIC analysed together)
   - $p_f > 11\%$ (3σ)
3. In the fast range $P = 0.011 - 1\,\mathrm{s}$ (pn only):
   - evidence at $P_\star$ = 18.6 ms (marginal but non-negligible! 3.8 σ)
   - pulsed fraction: $p_f = 13.5\%$
   - peak at $P_\star$ always highest in search when $E > 0.35\,\mathrm{keV}$ (*noisy read-out photons discarded)*
   - $Z_1^2(P_\star)$ power (significance) sensitive to the choice of:
     - energy band
     - extraction radii
   - consequence of varying S/N ratio as a function of energy

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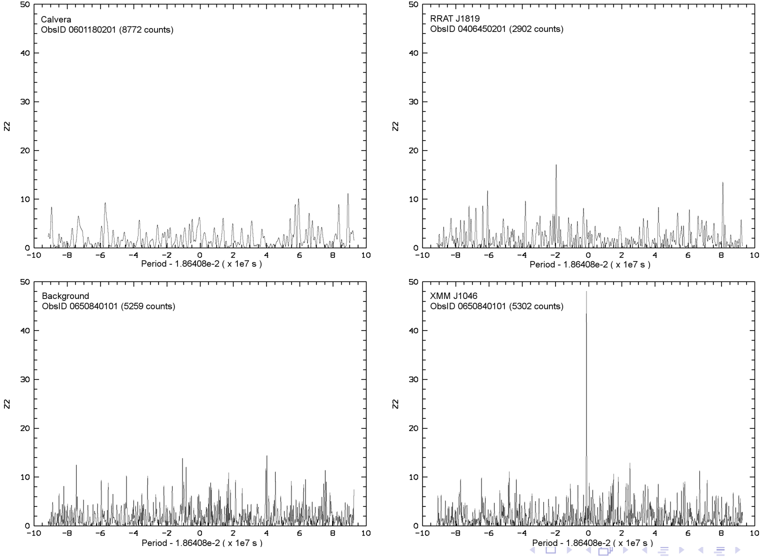
Not an instrumental effect!

Same analysis conducted on other observations in SW mode shows no peaks at $P_\star$

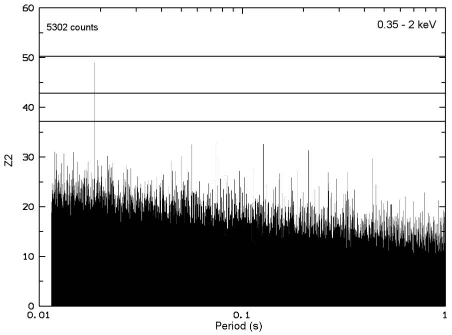


Tentative period at $P \sim 19\,\mathrm{ms}$ (3.8σ)

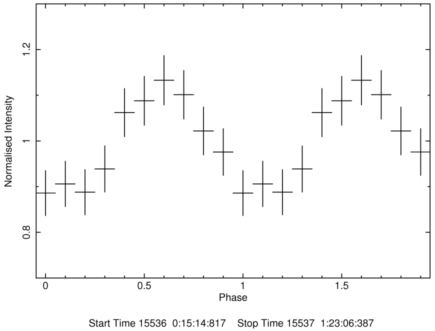
Results of Z_1^2 analysis in the "fast" regime $P = 0.011 - 1\,\mathrm{s}$

pn only, $\Delta\nu = 87.72\,\mathrm{Hz}$ and $\mathcal{N} = 5.55 \times 10^6$ independent trials

Periodogram Z_1^2



Folded light curve



Pires et al. 2011 (in prep.)

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Results: spectral analysis

1. Better constrained parameters, consistent with Pires'09
2. However, single component (absorbed) model hardly satisfactory
   - best fits: `bbody` and `nsa` with $\chi^2_\nu \sim 1.5$ (null hyp. prob. $< 1\%$)
   - `pow`: $\Gamma \sim 9$ too steep, considerably worse than thermal ($\chi^2_\nu \sim 2.4$)
   - residuals always around energies 0.6-0.7 keV and 1.3-1.4 keV
3. Better results when adding complexity (i.e. more components)
   - good fits when adding Gaussian absorption (under investigation)
   - tested `bb+bb`, `bb-gauss`, `bb+pl`, ...
   - double BB: soft component with very high R_∞
   - upper limits on PL hard tails: $< 1 - 2\%$ (3σ) to F_X

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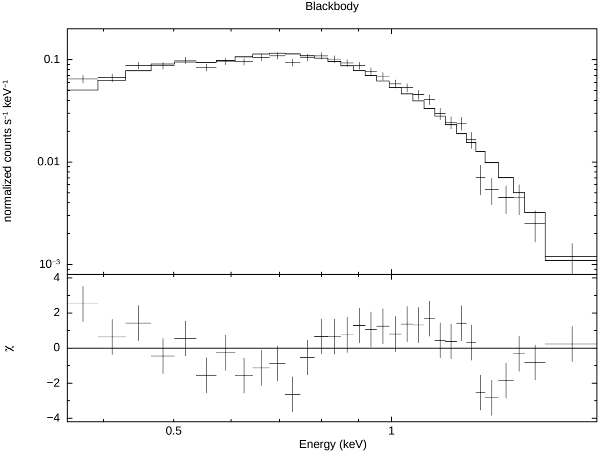
Single-component fit: structured residuals!



(only pn is shown)

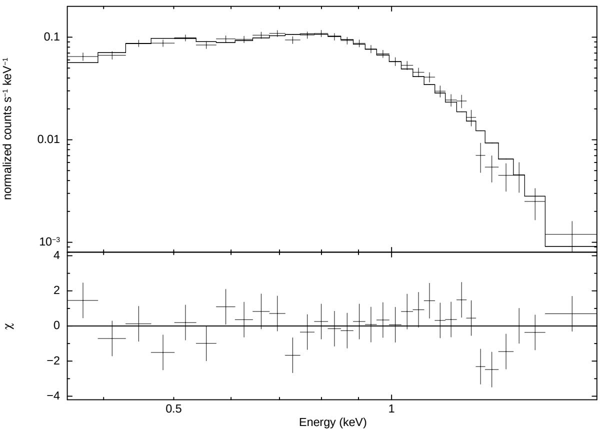
bbody

- $N_{\mathrm{H}} = 2.59^{+0.14}_{-0.21} \times 10^{21}\,\mathrm{cm}^{-2}$
- $kT_\infty = 136.1^{+4}_{-2.5}$ eV
- $R_\infty \sim 3$ km @ $d_{\eta Car} = 2.3$ kpc *($R_\infty \sim$ 2-7 km for the M7)*
- $\chi^2_\nu \sim 1.5$ ($<$ 1% for 63 dof)

1. excess softest bins
2. residuals at 0.6-0.7 keV and 1.3-1.4 keV

Adding complexity: improves agreement data-model

Blackbody − Gauss (Nh, sigma fixed)



(only pn is shown)

bbody−gauss

- fixed N_{H}
- $kT_\infty = 129.4^{+1.9}_{-1.7}$ eV
- $R_\infty \sim 4$ km
- $E = 0.589^{+0.017}_{-0.015}$ keV
- $\sigma = 0.1$ keV
- $\mathrm{EW} = -77$ eV
- $\chi^2_\nu \sim 1.1$ (32% for 62 dof)

1. O edge / O overab.(LOS)
2. residuals 1.3 keV remain

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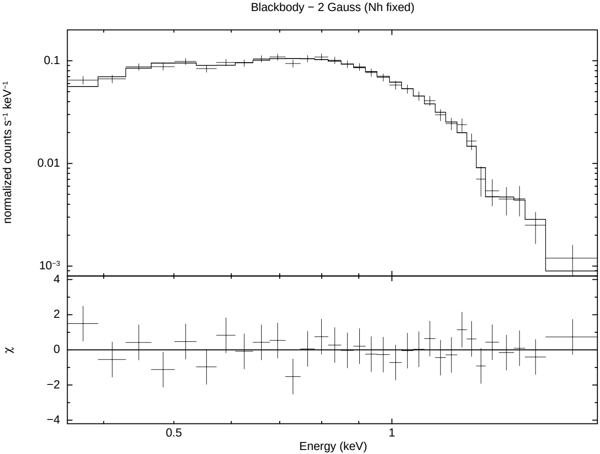
Adding complexity: improves agreement data-model



(only pn is shown)

`bbody-2*gauss`

- fixed $N_{\rm H}$
- $kT_\infty = 125^{+8}_{-5}$ eV
- $R_\infty \sim 4$ km
- $E_1 = 0.46^{+0.12}_{-0.24}$ keV
- $\sigma_1 = 0.18^{+0.06}_{-0.04}$ keV
- $\mathrm{EW}_1 = -0.14$ keV
- $E_2 = 1.36^{+0.03}_{-0.04}$ keV
- $\sigma_2 = 0.04^{+0.06}_{-0.04}$ keV
- $\mathrm{EW}_2 = -55$ eV
- $\chi^2_\nu \sim 0.93$
  (63% for 58 dof)

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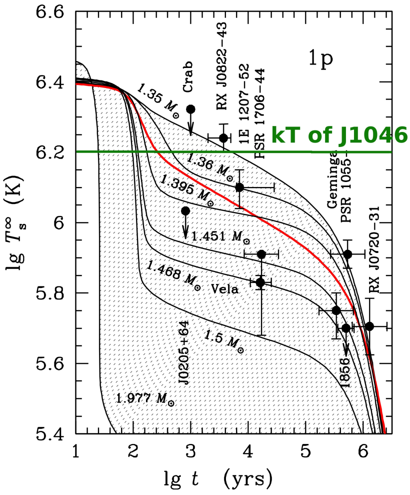
High kT for standard cooling?

No SNR $\longrightarrow$ age $\gtrsim 10^4$ yr



Cooling curves from Yakovlev & Pethick 2004 (including proton superfluidity)

XMM J1046: a unique isolated neutron star

Giant nebula might harbour other neutron stars
(c.f. Townsley et al. 2011)

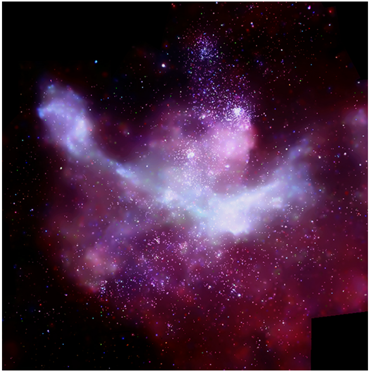


Image courtesy of NASA/CXC/PSU/L.Townsley et al.

1. Missing links beginning to emerge
   - magnetar with low $B_{\rm dip}$ *(Rea et al. 2010)*
   - radio-loud magnetar in X-ray quiescence *(Levin et al. 2010)*
   - orphan CCO *(Calvera; Zane et al. 2011)*

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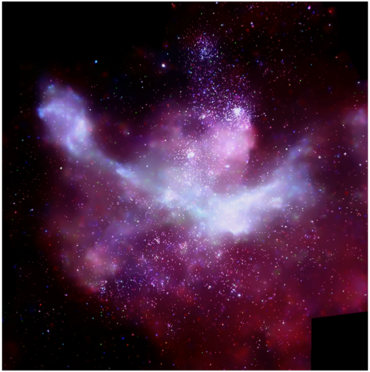

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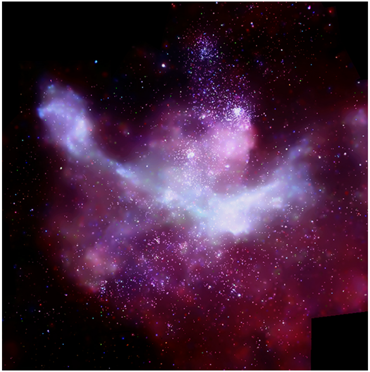

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3. Tentative spin period: very fast, 19 ms
   - analogy to Calvera (old CCO)?
   - in Carina: not recycled?
   - confirm P, constrain $\dot{P}$ and B!

Chimera type of object. . .

Provided by S. Popov

Thank you!