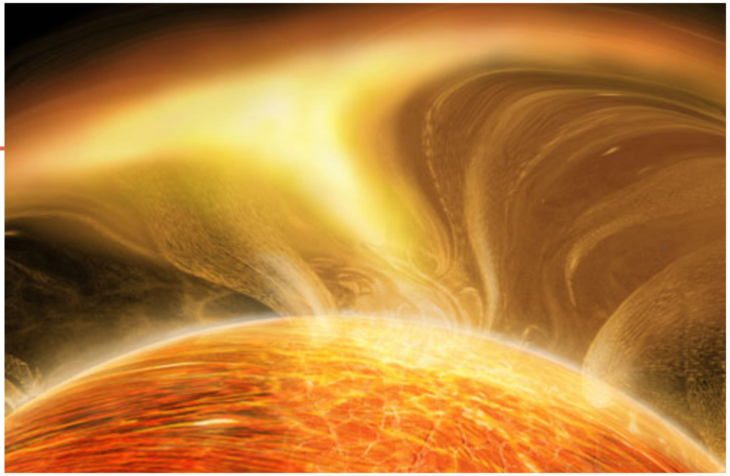
MAGNETARS: NEUTRON STARS IN THE EXTREME



R Turolla
Department of Physics and Astronomy
University of Padova, Italy

with lot of help from P. Esposito, G.L. Israel, S. Mereghetti, L. Nobili, J. Pons, N. Rea, R. Taverna, A. Tiengo, S. Zane and many others

Outline

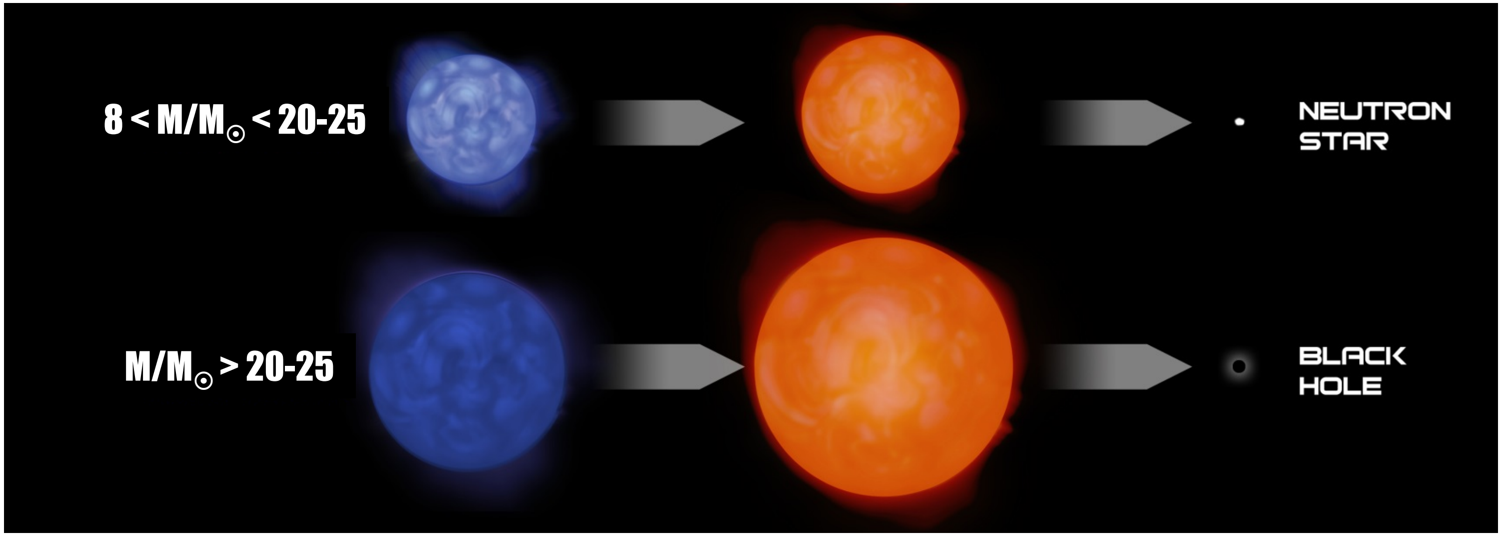
- Neutron stars in a nutshell
  - The Galactic NS population
  - NS structure
  - Rotation and magnetism
  - Different classes of (isolated) NSs
- Soft Gamma Repeaters (SGRs) and Anomalous X-ray pulsars (AXPs)
  - General properties
  - SGRs & AXPs as magnetars (aka ultra-magnetized NSs)
- The persistent X-ray emission
  - X-ray spectra
  - The twisted magnetosphere model

Outline - II

- Bursts & Flares
  - Burst phenomenology
  - Burst triggers and emission
- What makes a magnetar ?
  - SGRs/AXPs vs. high-field pulsars
  - “Low-field” magnetars (?)
  - NSs magneto-thermal evolution
  - The case of SGR 0418+5729
  - A magnetar orbiting the CG SMBH

Neutron Star Basics

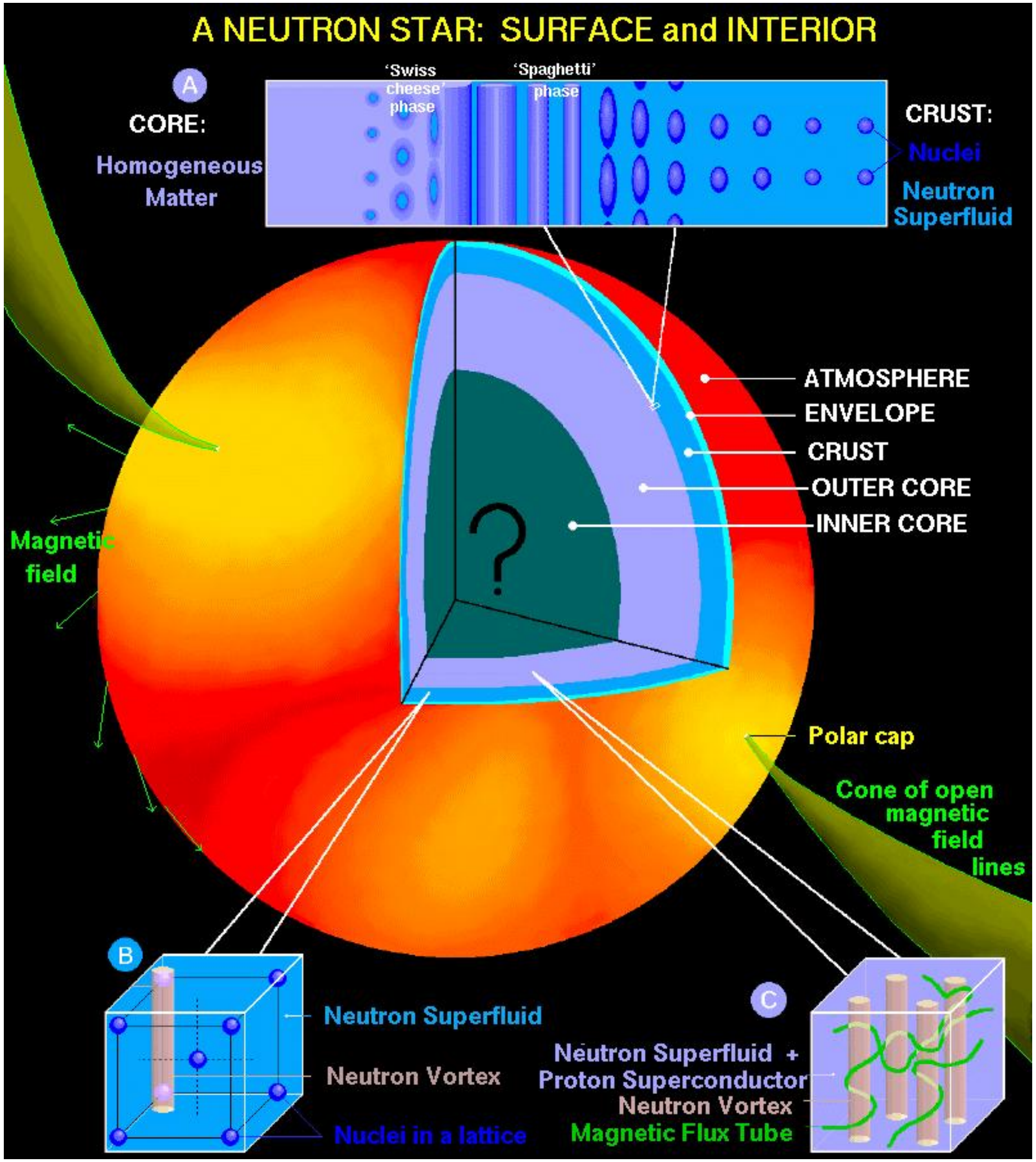
- Neutron stars (and black holes) are born in the core collapse following a supernova explosion
- Present rate of SN events in the Galaxy: ≈ 0.01/yr (possibly higher in the past)
- Galactic population of compact objects: ≈ 10^8 – 10^9 (≈ 1% of stars)
- Nature of compact remnant depends on progenitor mass



- If $N(>M) \sim M^{-1.3}$ (Salpeter) only ~ 20% of stars with $M > 8\ M_\odot$ are more massive than $25\ M_\odot$
- Very massive stars may form “magnetars” (Muno et al 2006, but see also Clark et al. 2014), black holes about 10% of the total
- Galactic compact objects are mostly neutron stars ($\approx 10^8$)

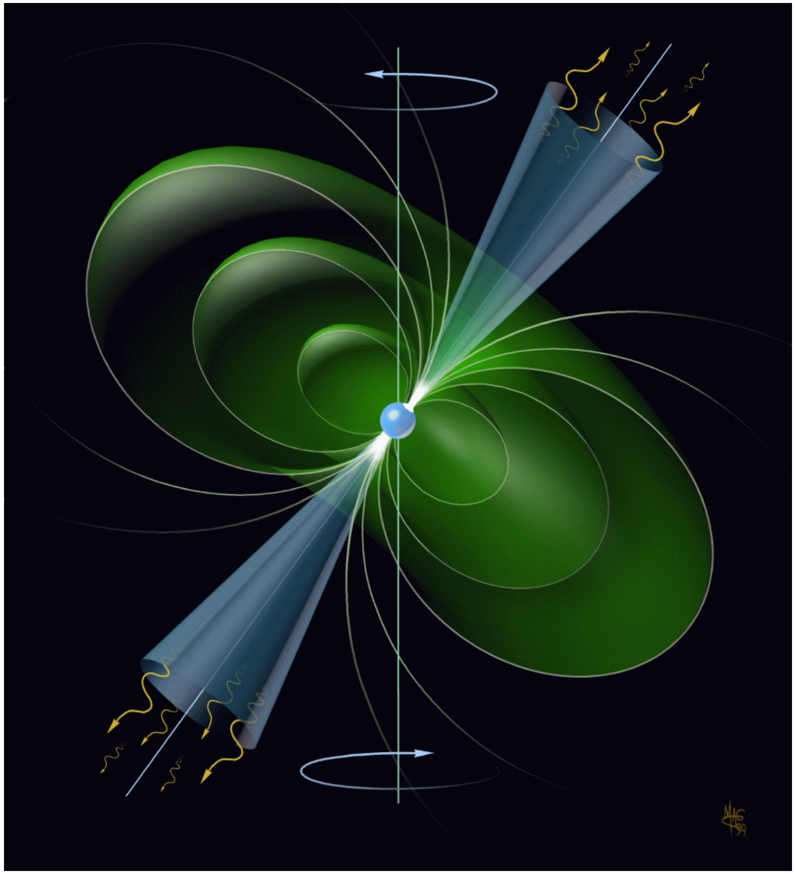
Masses ~ 1 – 2 $M_\odot$
Radii ~ 10 – 15 km (~ 3 Schwarzschild radii)
Central density ~ 10^{15} g/cm^3
Surface gravity ~ $10^{14\text{-}15}$ cm/s^2

A 10 km sphere made of neutron superfluid covered by few hundred meters of ordinary matter with a 10 cm gaseous atmosphere on top (with a big question mark near the centre)



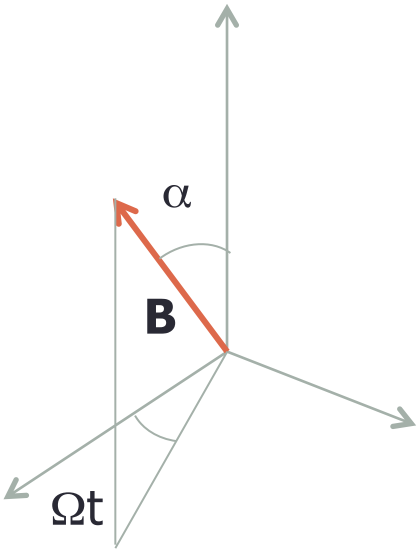
Rotation and Magnetism

- NSs rotate fast (fastest known: PSR J1748-2446ad, ν=716 Hz, P=1.4 ms)
- Large dipole magnetic field (B ≈ 10^{12} G in "normal" PSRs)
- Spin-down by magneto-dipolar losses



- A rotating magnetic dipole radiates at a rate

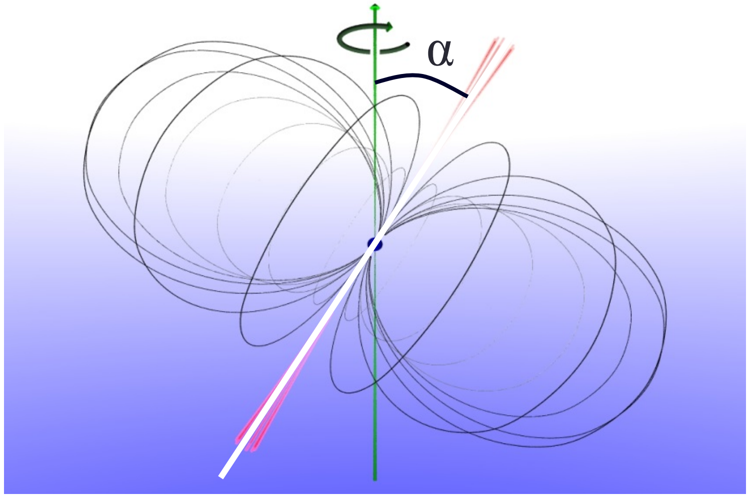
$$\dot{E} = -\frac{2}{3c^3}\left|\ddot{\vec{m}}\right|^2$$



$$\vec{m} = \frac{1}{2}B_p r^3\left(\sin\alpha\cos\phi, \quad \sin\alpha\sin\phi, \quad \cos\alpha\right)$$

$$\phi = \Omega t$$

$$\left|\ddot{\vec{m}}\right| = \Omega^2 \sin\alpha\left|\vec{m}\right|$$



Total NS rotational energy $E = \frac{1}{2} I \Omega^2$

$$\dot{E} = I\Omega\dot{\Omega} = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

$$\frac{1}{2}\left(\frac{1}{\Omega^2} - \frac{1}{\Omega_0^2}\right) = \frac{t - t_0}{\tau\,\Omega^2}, \quad \tau = \frac{6Ic^3}{B_p^2 R^6 \Omega^2 \sin^2\alpha}$$

$$\Omega << \Omega_0 \Rightarrow t - t_0 = \tau/2 \qquad \frac{P}{\dot{P}} = \tau$$

$$B_p \sin\alpha = 6.4\times10^{19}\, R_6^{-3} I_{45}^{1/2} \left(P\dot{P}\right)^{1/2}\ \mathrm{G}$$

Measuring P and Ṗ is crucial

P

$B \sim 3 \times 1$

$\dot{E} \sim 1.3 \times$

P$_0$ << P!

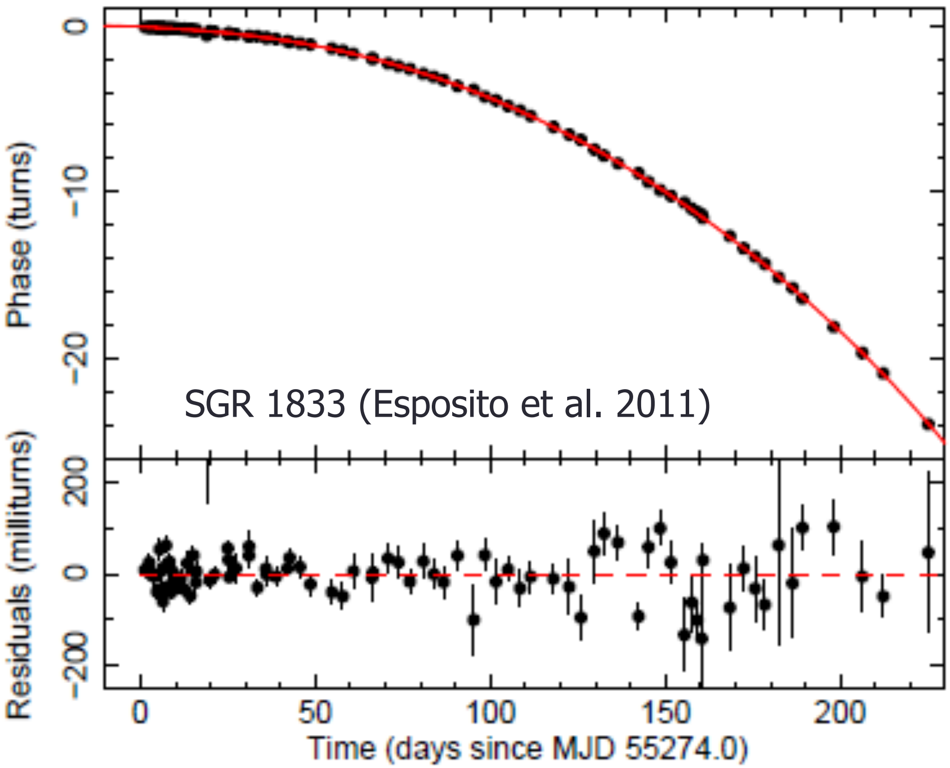
Phase-c

riodic

$\phi(t) = \int_t$

$)^2 + \dots$

$= \phi$



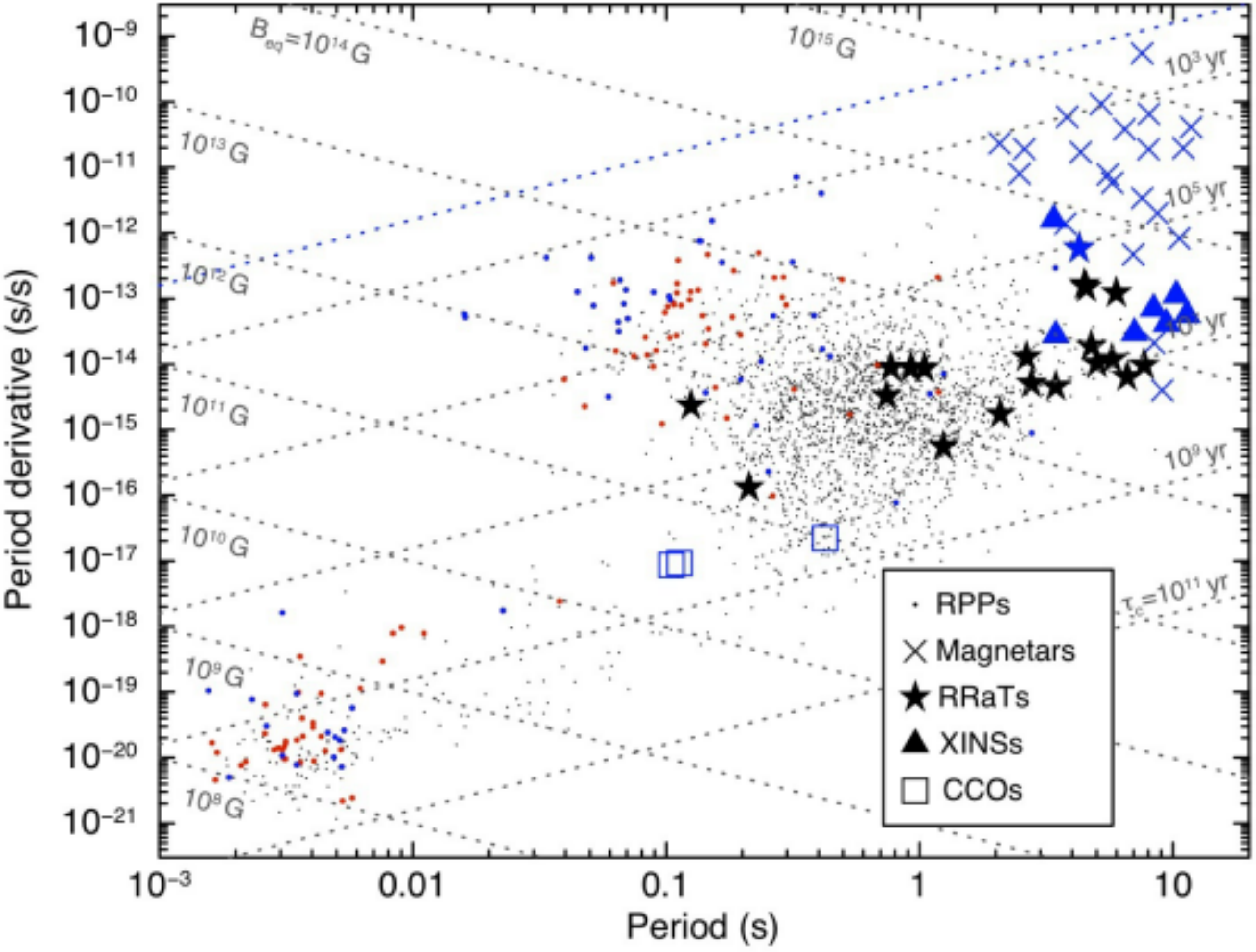
SGR 1833 (Esposito et al. 2011)

Pulsars and…

- Most neutron stars are known through their pulsed radio-emission
- Galactic pulsar population ≈ 10^5 (Vranisevic et al. 2004; > 2000 detected, ATNF catalogue)
- The majority of neutron stars are old, dead objects
- Observations in the X- and γ-rays revealed the existence of different classes of isolated neutron stars
  - Central compact objects in SNRs (CCOs)
  - X-ray dim isolated neutron stars (XDINSs)
  - Rotating Radio Transients (RRaTs)
  - Soft γ-repeaters (SGRs)
  - Anomalous X-ray pulsars (AXPs)

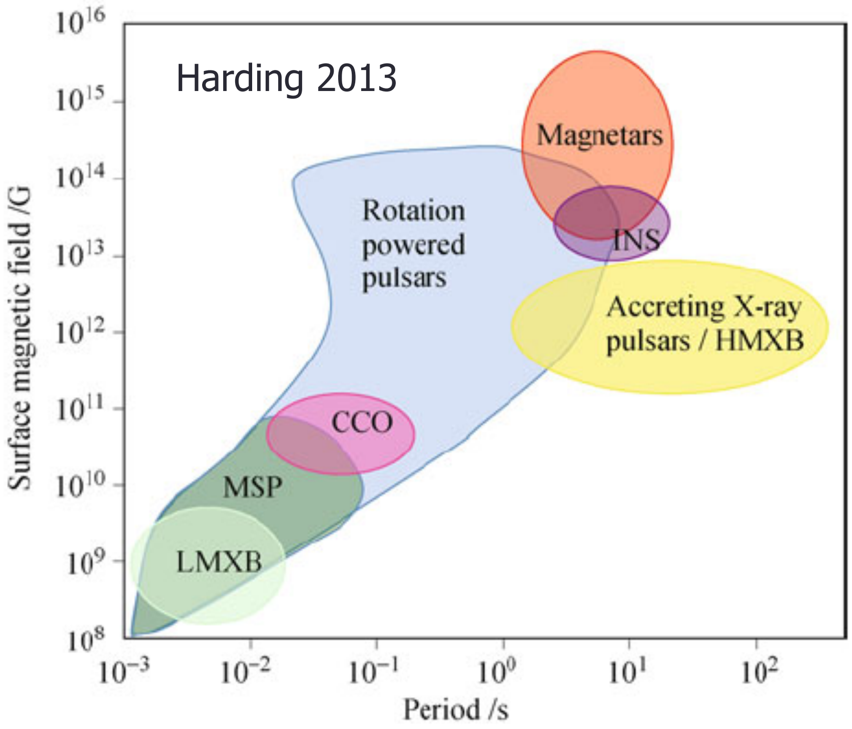
→ Magnetars

The P - Ṗ Diagram



The Powerhouse

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



Are There Enough SNe ?

- Core-collapse supernova rate, $\beta_{CCSN} = 1.9 \pm 1.1$ century^{-1}
- PSRs birth rate, $\beta_{PSR} \sim 1.4$ century^{-1}
- RRaTs birth rate, $\beta_{RRAT} > 4$ century^{-1}
- Magnetars birth rate, $\beta_{Mag} \sim 0.1$ century^{-1}
- CCOs birth rate, $\beta_{CCO} \sim 0.04$ century^{-1}
- XDINSs birth rate, $\beta_{XDINS} \sim 2$ century^{-1}

Total NS birthrate

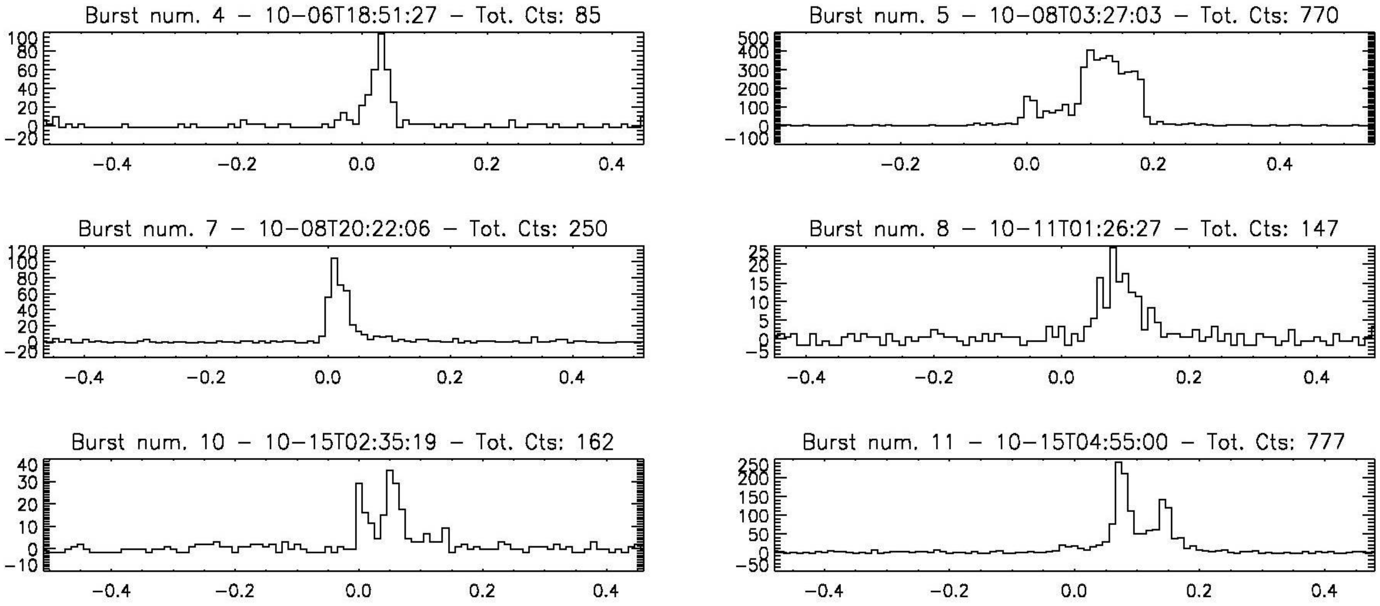
$\beta_{TOT} \sim 1.4+4+0.1+0.04+2 = 6.5$ century^{-1} $> \beta_{CCSN}$

EVOLUTION !

Soft Gamma Repeaters - I

Rare class of sources, discovered through the emission of strong, recurrent (whence the name) bursts of soft γ-/ hard X-rays:

L ≈ 10^{39}-10^{41} erg/s >> L_{Edd}, duration 0.1 - 1 s



Bursts from SGR 1806-20 (INTEGRAL/IBIS,Gőtz et al 2004)

Soft Gamma Repeaters - II

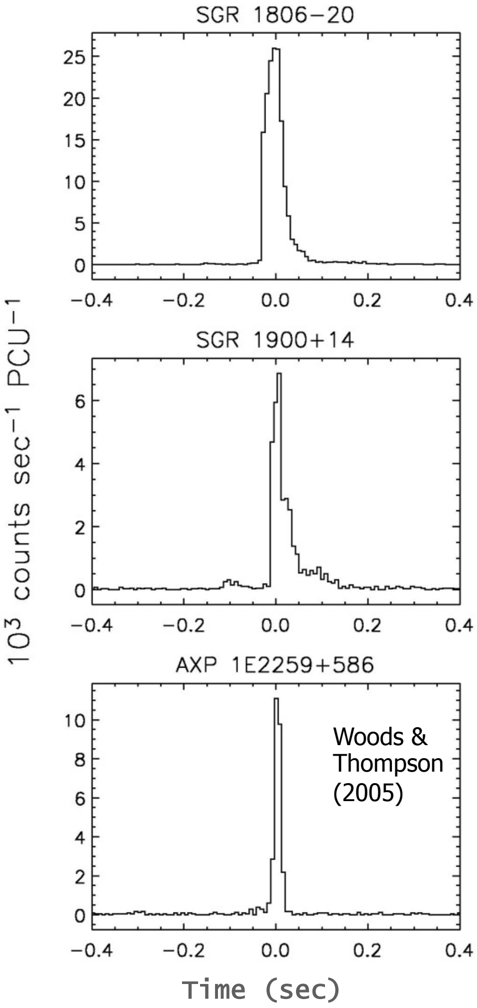
- Much more energetic “Giant Flares” (GFs, $L \approx 10^{44} - 10^{47}$ erg/s, $t_{peak} \sim 1$ s, $t_{tail} \sim 300$ s) detected from 3 sources
- No evidence for a binary companion, association with a SNR in 1 (?) case
- Persistent X-ray emitters, $L \approx 10^{33} - 10^{35}$ erg/s
- Pulsations discovered both in GFs tails and persistent emission, $P \approx 2 - 10$ s
- Huge spin-down rates, as compared to PSRs, $\dot{P} \approx 10^{-11} - 10^{-10}$ ss^{-1}

Anomalous X-ray Pulsars - I

- Peculiar class of persistent X-ray sources, $L \approx 10^{33} - 10^{35}$ erg/s
- Spin-down luminosity $\dot{E} < L_X$ (not powered by rotation, hence "anomalous")
- Pulsations with $P \approx 2 - 10$ s
- Large spin-down rates, $\dot{P} \approx 10^{-11}\ \mathrm{ss}^{-1}$
- No evidence for a binary companion, association with a SNR in six (?) cases

Anomalous X-ray Pulsars - II

- Bursts of soft γ-/hard X-rays quite similar to those of SGRs detected first in AXP 1E 2259+586 (Gavriil et al. 2002; Kaspi et al. 2003) and then in all (but one) AXPs



Woods & Thompson (2005)

A tale of Two Populations ?

Positions of currently known AXPs and SGRs

- Several clues indicate that these are (isolated) neutron stars
    - $R < ct_{rise} \approx 100$ km
    - pulsations

Magnetars

- Strong convection in a rapidly rotating (P ~ 1 ms) newborn neutron star generates a very strong magnetic field via dynamo action
- Magnetars: neutron stars powered by their own magnetic energy (surface field B > a few $B_{QED} \sim 10^{14}$ G; Duncan & Thomson 1992; Thomson & Duncan 1993)
- Rapid spin-down due to magneto-dipolar losses, $P = 10^{-11} \left(B/10^{14}\ G\right)^{2} P^{-1}\ s/s$

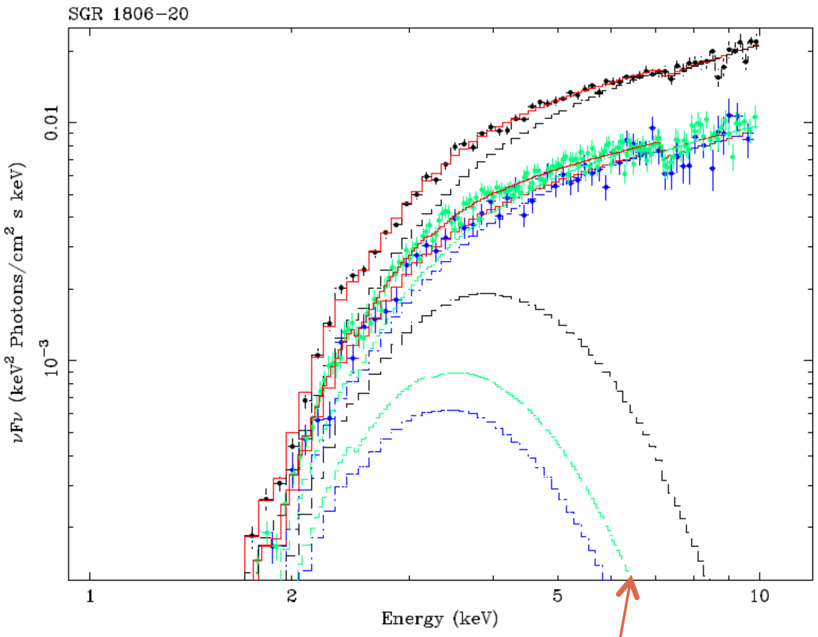
Why magnetars ?

- $L_X > \dot{E}$ → not powered by rotation
- No evidence for a companion star → not powered by accretion
- Quite young objects (≈ 10^3 - 10^4 yrs): spin down to present periods (a few seconds) requires $B > 10^{14}$ G
- Large measured spin-down rates
- Giant flares energetics requires $B > 10^{15}$ G
- Opacity suppression for the X polarization mode in a strong B-field explains the large, super-Eddington flux in bursts

No direct measure of a super-strong field until recently

SGRs and AXPs X-ray Spectra

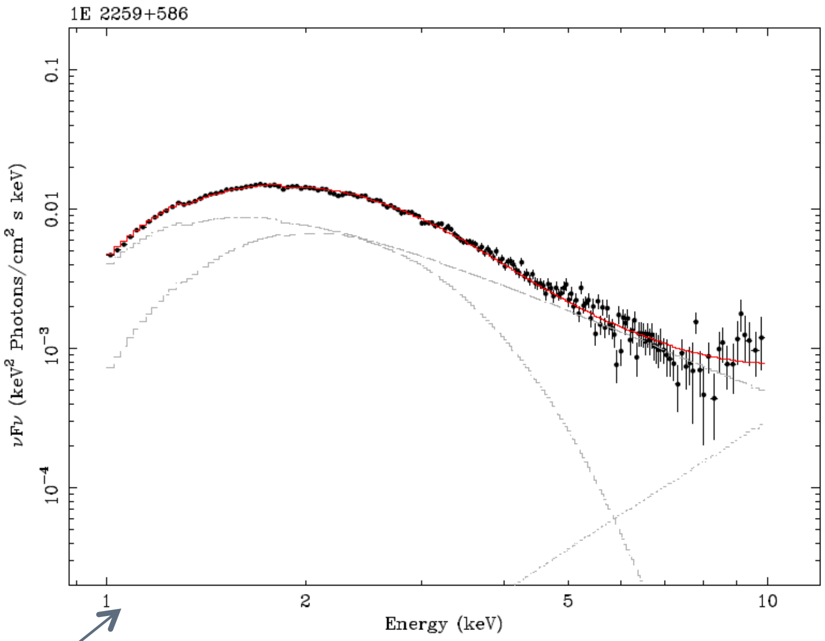
- 0.5 – 10 keV emission well represented by a blackbody plus a power law
- $kT_{BB} \sim 0.5$ keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$, AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/ years)
- Variability mostly associated with the non-thermal component
- Transient spectra can be BB+BB, T_{BB} and R_{BB} decrease in time

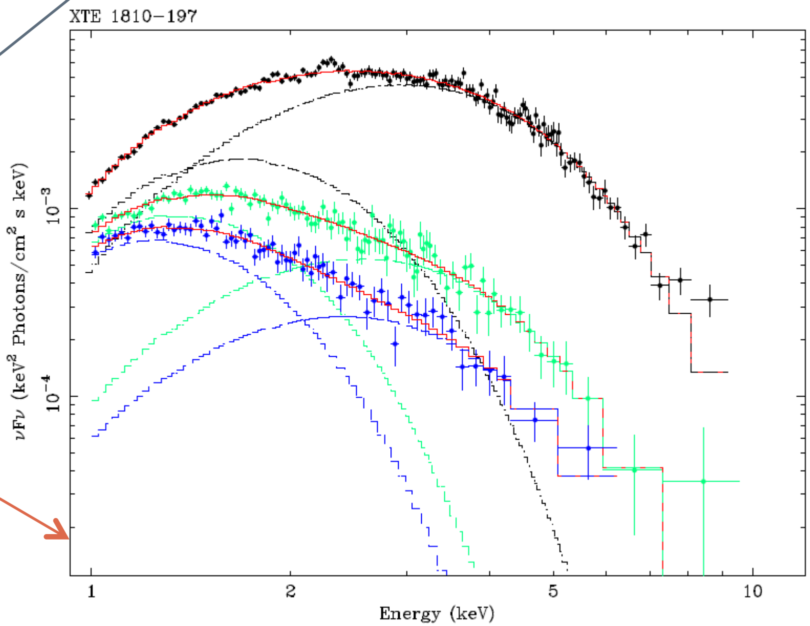


SGR 1806-20 at different epochs (BB+PL)

AXP 1E 2259-586 (BB+PL)

Transient AXP XTE 1810-197 at different epochs (BB+BB)





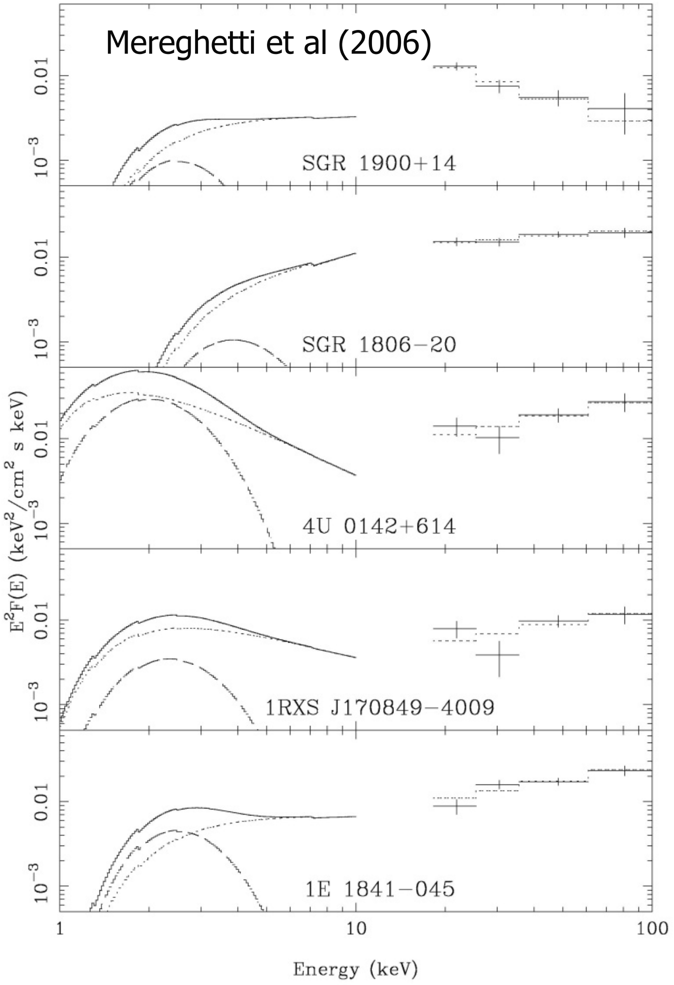
XMM Epic-pn data (Rea el al. 2008)

Hard X-ray Emission

INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and AXPs

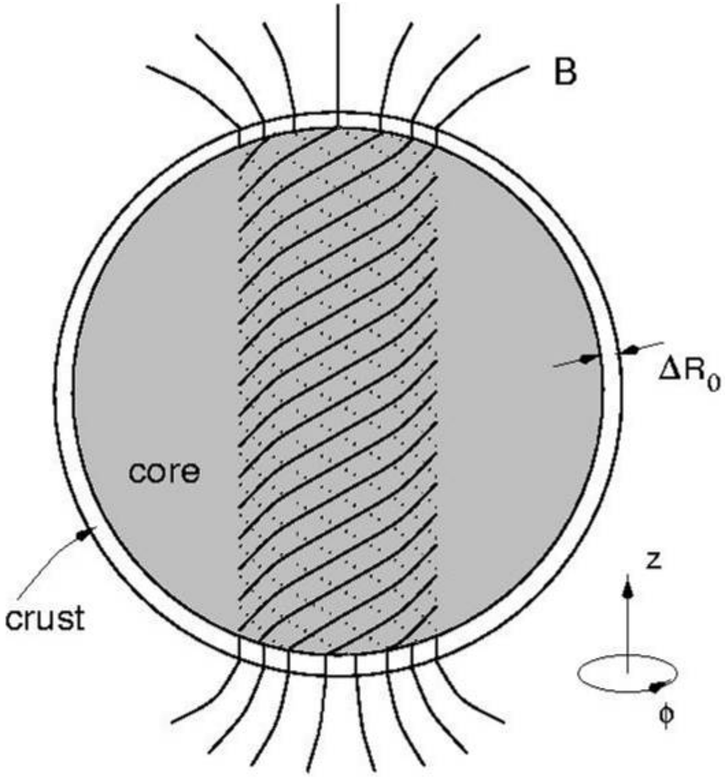
Hard power law tails with Γ ≈ 1-3, hardening wrt soft X-ray emission required in AXPs

Hard emission highly pulsed


Mereghetti et al (2006)

Twisted Magnetospheres – I

- The magnetic field inside a magnetar is “wound up”
- The presence of a toroidal component induces a rotation of the surface layers
- The crust tensile strength resists
- A gradual (quasi-plastic ?) deformation of the crust
- The external field twists up
(Thompson, Lyutikov & Kulkarni 2002)

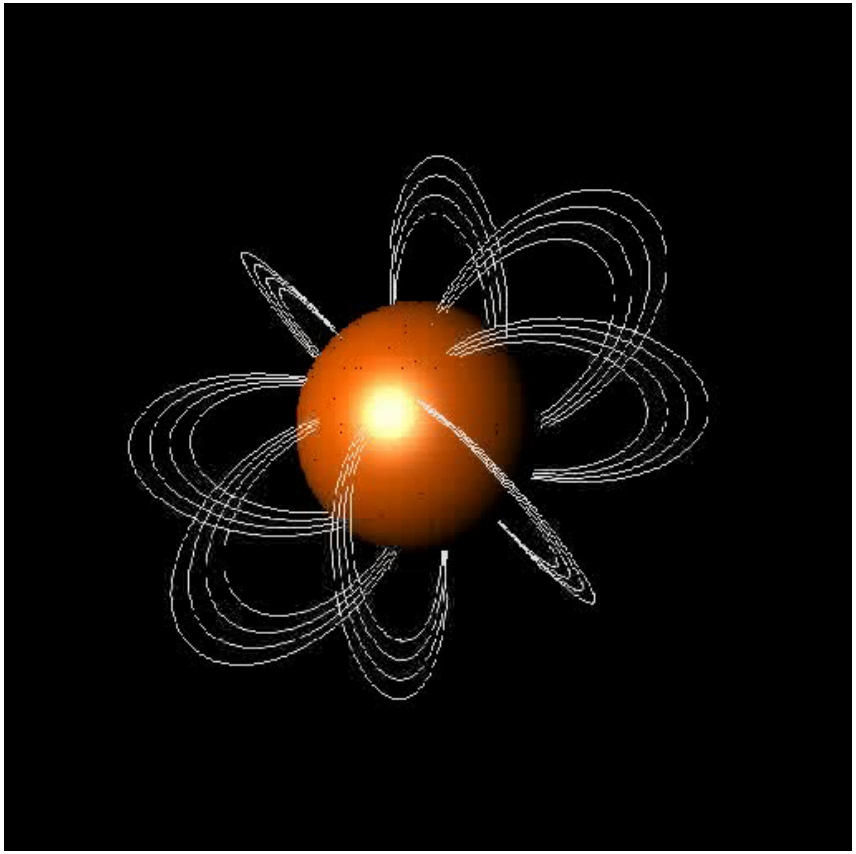


Thompson & Duncan (2001)

Twisted Magnetospheres - II

- Twisted fields are non-potential, $\nabla \times \vec{B} \neq 0$
- Globally twisted dipole (Thompson, Lyutikov & Kulkarni 2002, Pavan et al. 2009)
- A sequence of models labeled by the twist angle

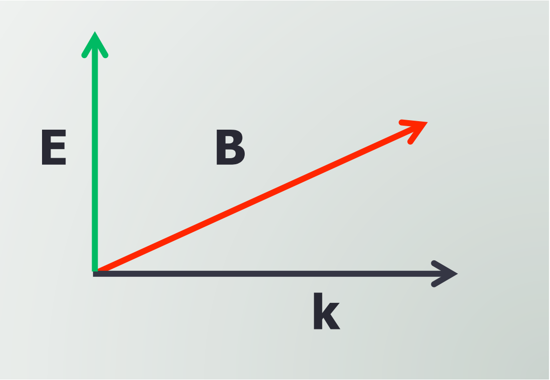
$$\Delta\phi_{N-S} = 2\int_0^{\frac{\pi}{2}} \frac{B_\phi}{B_\theta} \frac{d\theta}{\sin\theta}$$



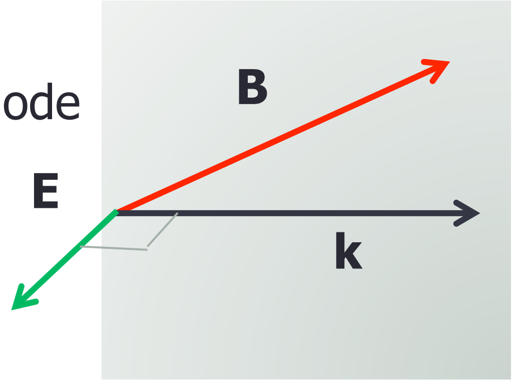
Photons in a Magnetized Medium

- A magnetized plasma is anisotropic and birefringent, radiative processes sensitive to polarization state
- Two normal, linearly polarized modes in the magnetized vacuum: the extraordinary (X) and ordinary (O) mode
- Opacities greatly reduced for X-mode photons

O mode



X mode



The electron scattering cross section in the ERF is resonant at the cyclotron frequency and its harmonics

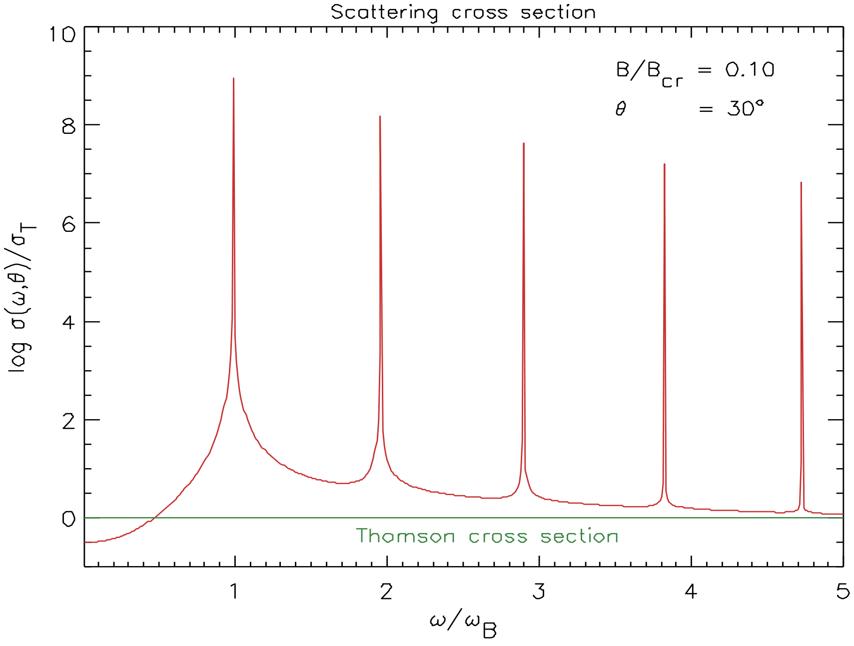
$$E_n = n\hbar\omega_B = n\frac{eB}{mc}$$

For an electron moving with velocity β the (first) resonance is at a frequency

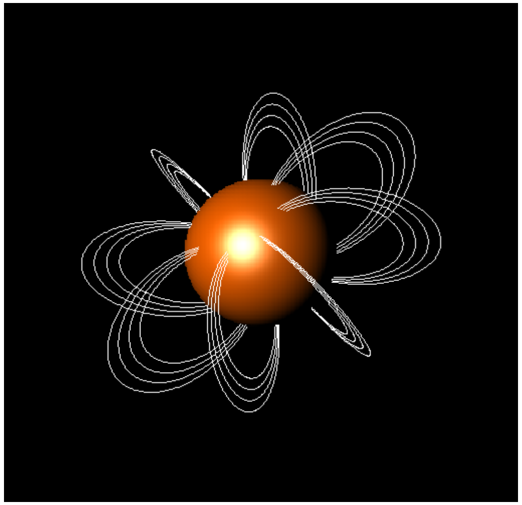
$$\omega_D = \frac{\omega_B}{\gamma\left(1-\beta\cos\theta\right)}$$

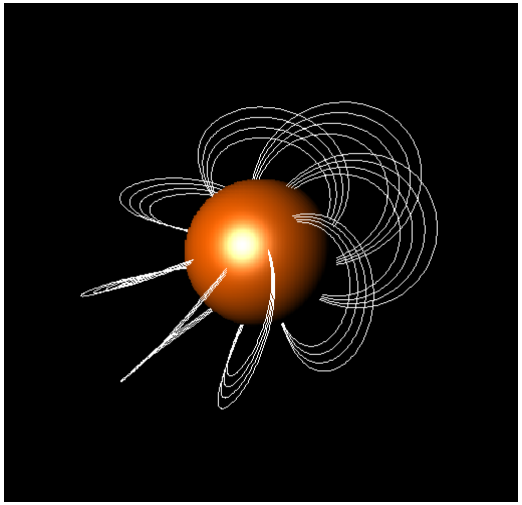
$$\sigma_{1-1} = \frac{1}{3}\sigma_{1-2} = \frac{\pi^2 r_0 c}{2}\delta(\omega-\omega_D)\cos^2\theta_{\mathrm{ERF}}$$

$$\sigma_{2-2} = 3\sigma_{2-1} = \frac{3\pi^2 r_0 c}{2}\delta(\omega-\omega_D),$$



Magnetospheric Currents - I





$$\nabla \times B = 0$$

$$j = \frac{c}{4\pi} \nabla \times B$$

Contrary to PSRs, currents flow (also) along the closed field lines and $j \gg j_{GJ}$

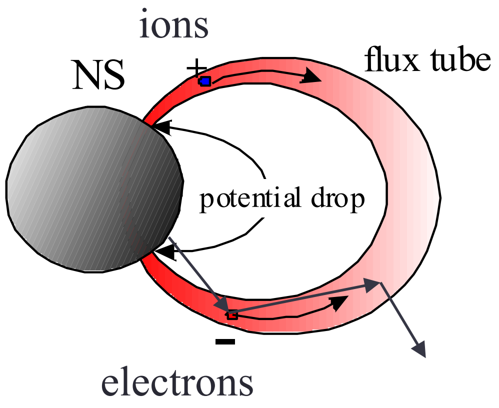
Magnetospheric Currents - II

The twist must decay to support its own currents. A parallel electric field develops which accelerates the charges along the flux tube (Beloborodov & Thompson 2007; Beloborodov 2009)

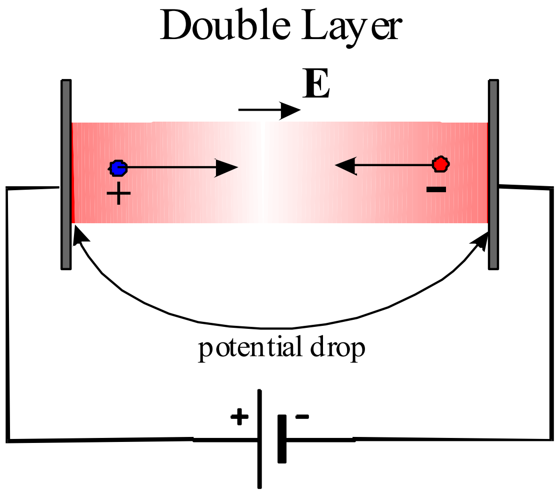
$$\frac{\partial(B_\phi^2/8\pi)}{\partial t} = -E_{||} j \qquad \frac{\partial E_{||}}{\partial t} = j - j_B$$

The electric field is self-regulated to ensure that the required current flows in the circuit

A potential drop Φ is maintained between the footpoints j = j(Φ) depends on the nature of the discharge and this fixes the duration of the twist



A simple analogue



In a relativistic double layer $j \propto \frac{m_e}{m_i}\Phi^2, \gamma_e \approx 1 + \frac{e\Phi}{m_e c^2}$

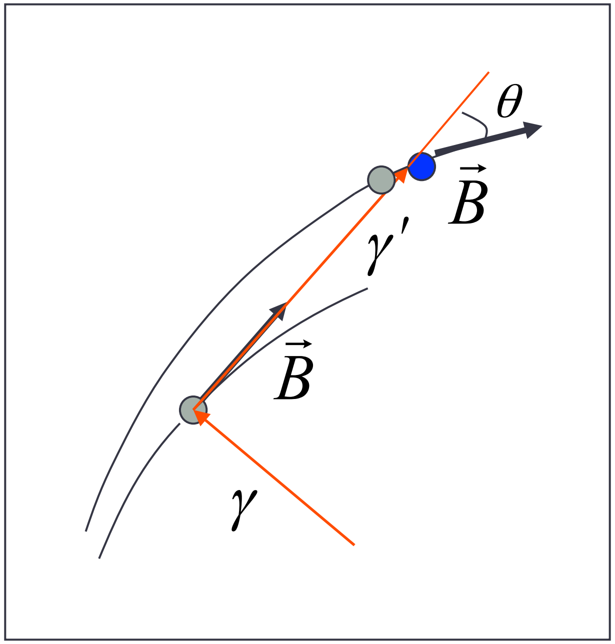
Φ (and $E_\parallel$) must be huge ($\approx 10^{12}$ GeV) in order to produce j_B:
$\gamma_e \approx 10^9$ and the twist decays immediately

Where B > $2B_Q$, 1 keV photons scatter onto γ > 1000 electrons Scattered photons have energy ε' in the MeV range and initially propagate along B

They quickly convert into pairs via

$$\gamma + B \rightarrow e^{+} + e^{-} + B$$

as soon as $\varepsilon' > \frac{2m_e c^2}{\sin\theta}$



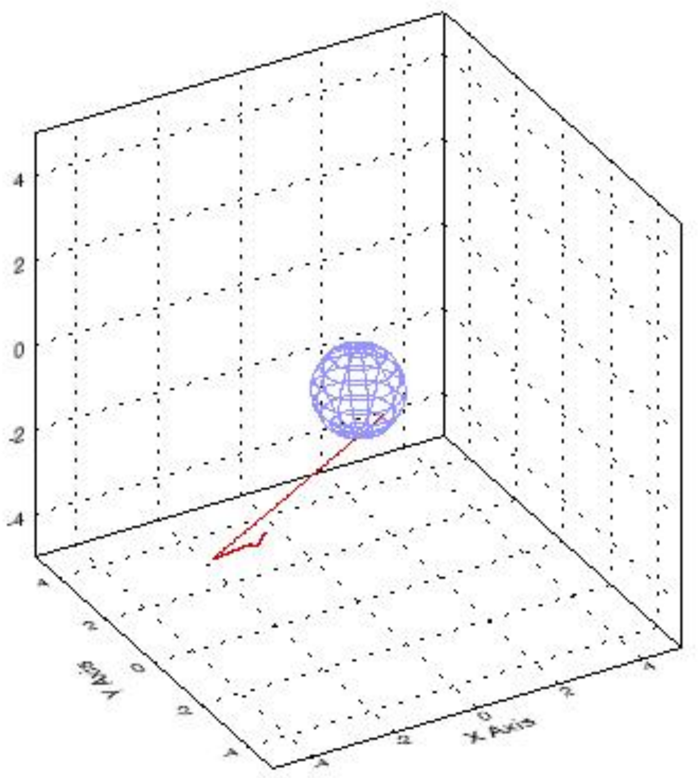
Pair production along the entire circuit screens the potential: j_B can be conducted with $\Phi \ll \Phi_{DL}$

A quasi-stationary state in which the particle energy is just that required to ignite the pair cascade (Beloborodov & Thompson 2007)

Resonant Compton Scattering

- The current flowing along the closed field lines is

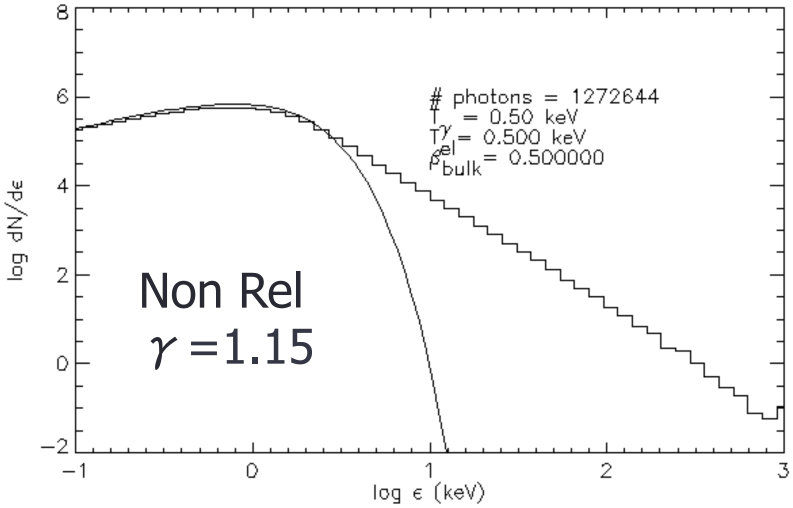
$j=(c/4\pi)\nabla\times B\Rightarrow n\downarrow e=p+1/4\pi e\, B\downarrow\varphi\, /B$



- The optical depth for Thoms
$n_e\sigma_T r \approx 10^{-4}$
- At resonance $\sigma \approx 10^5\ \sigma_T \rightarrow$
resonant cyclotron scatterin
- Up-scattering of thermal ph
cooling surface onto mildly

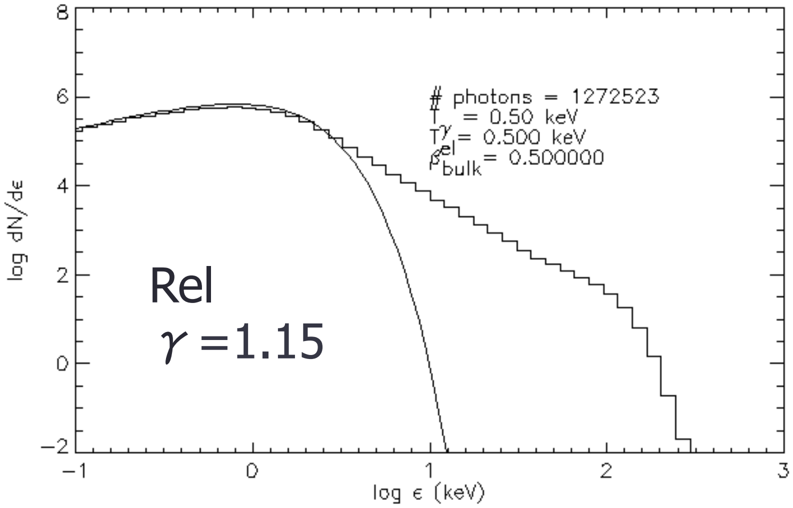
Repeated scatterings lead to the formation of a power-law tail because $\omega_D = \omega_D(r,\theta)$ and $r_{current} > R_{NS}$

Spectral formation in twisted magnetospheres investigated quite in detail using Montecarlo methods (Lyutikov & Gavriil 2006; Fernandez & Thompson 2007; Nobili, Turolla & Zane 2008a, b)



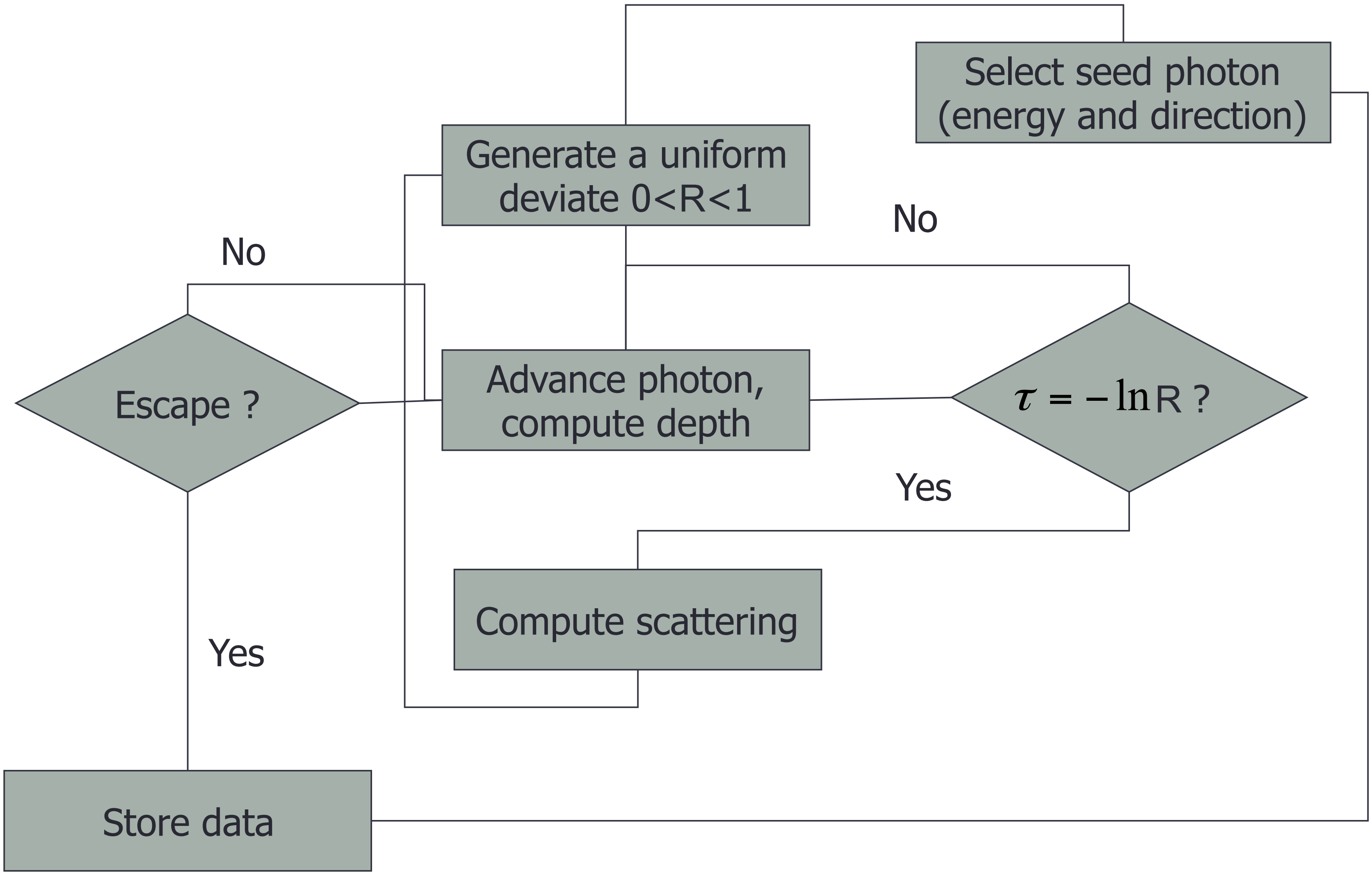
Non Rel

$\gamma = 1.15$



Rel

$\gamma = 1.15$


Select seed photon (energy and direction)

Generate a uniform deviate 0<R<1

Advance photon, compute depth

$\tau = -\ln R$?

No

Yes

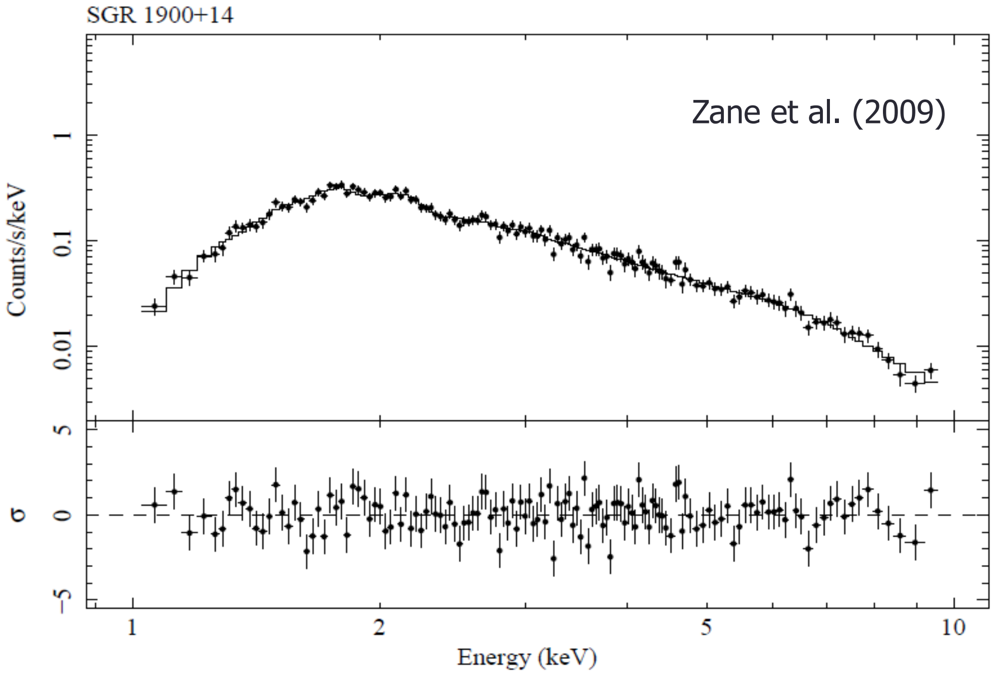
Compute scattering

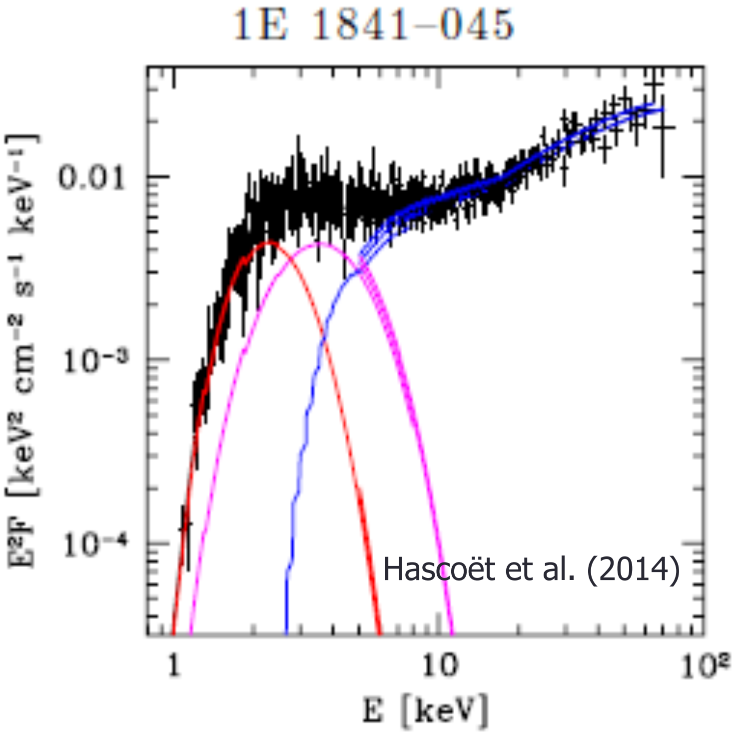
Escape ?

No

Yes

Store data


Zane et al. (2009)


Hascoët et al. (2014)

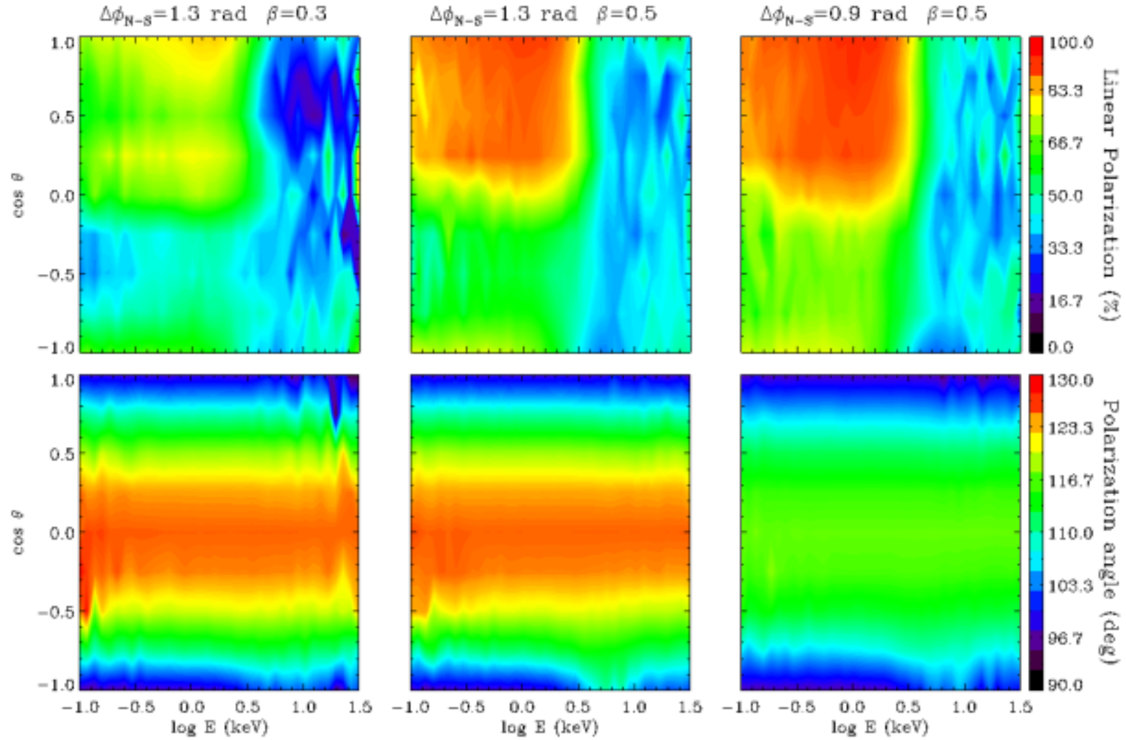
RCS models quite successful in explaining magnetars soft X-ray spectra (~ 0.5 – 10 keV) and also high-energy tails

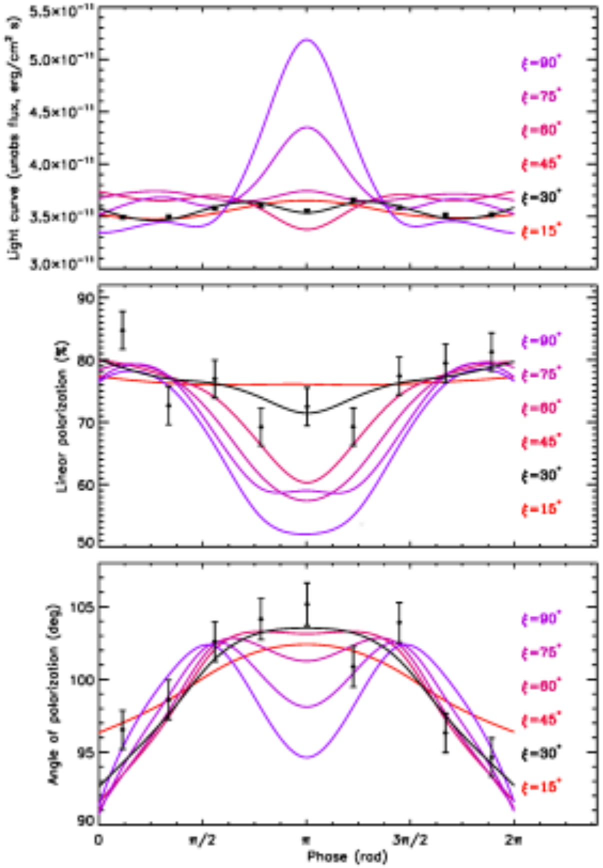
Spectral fits provide information on the physical state of the star/magnetosphere (twist angle, charge velocity, surface temperature, etc)

No single spectral model can consistently explain observations in the 0.5-100 keV band though

X-ray Polarization

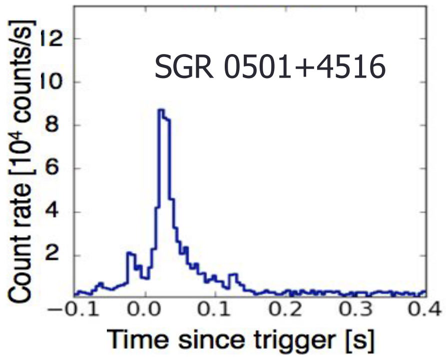
- Thermal surface emission highly polarized in the X-mode
- Scatterings can change the photon polarization state
- The observed polarization fraction and polarization angle depend on QED effects ("vacuum polarization") and on magnetic field geometry (Stokes parameters rotation)
- Π_L and χ_p very sensitive to the source geometry (inclination of the LOS and of the magnetic axis wrt the rotation axis)
- X-ray polarimetry will provide an entirely new tool in magnetar studies
- XIPE and IXPE proposed for ESA M4 and NASA Smex programmes

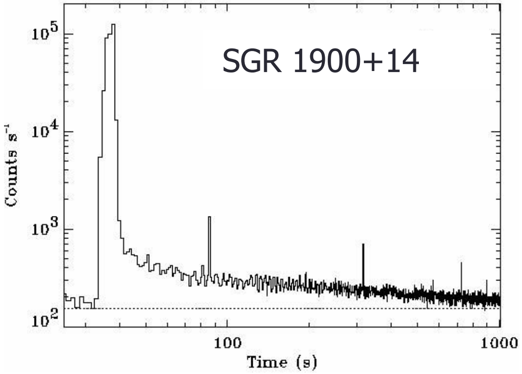

$\Delta\phi_{N-S}$=1.3 rad β=0.3
$\Delta\phi_{N-S}$=1.3 rad β=0.5
$\Delta\phi_{N-S}$=0.9 rad β=0.5
cos θ
1.0
0.5
0.0
−0.5
−1.0
log E (keV)
−1.0
−0.5
0.0
0.5
1.0
1.5
Linear Polarization (%)
100.0
83.3
66.7
50.0
33.3
16.7
0.0
Polarization angle (deg)
130.0
123.3
116.7
110.0
103.3
96.7
90.0

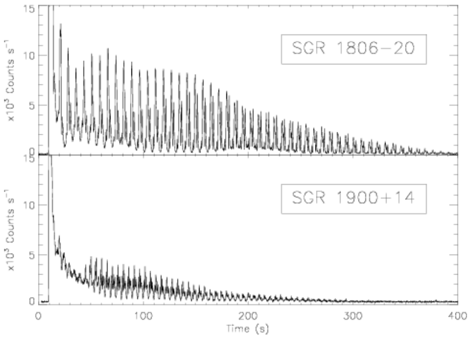

Light curve (unabs flux, erg/cm² s)
5.5×10⁻¹¹
5.0×10⁻¹¹
4.5×10⁻¹¹
4.0×10⁻¹¹
3.5×10⁻¹¹
3.0×10⁻¹¹
Linear polarization (%)
90
80
70
60
50
Angle of polarization (deg)
105
100
95
90
ξ=90°
ξ=75°
ξ=60°
ξ=45°
ξ=30°
ξ=15°
0
π/2
π
3π/2
2π
Phase (rad)

Bursts & Flares

- Short bursts
  - t ~ 0.1 – 1 s, L ~ 10^{39} – 10^{41} erg/s , thermal spectrum (kT ~ 10 keV), seen in both SGRs and AXPs
- Intermediate bursts
  - t ~ 1 – 40 s, L ~ 10^{41} – 10^{43} erg/s , thermal spectrum, seen in both SGRs and AXPs
- Giant flares
  - only three observed, each from a different SRG, L ~ 10^{44} – 10^{47} erg/s, initial spike (~ 0.1s) + pulsating tail (~ 100 s)







Burst Trigger Mechanism(s)

Rapid magnetic field reconfiguration is a key ingredient, but no precise model as yet

Secular magnetic evolution builds stresses that are released catastrophically in the bursts

Alvén speed
$$v_A = 10^8 \mathrm{cm/s} \left(\frac{B}{10^{16}\mathrm{G}}\right) \left(\frac{10^{15}\mathrm{g/cm}^3}{\rho}\right)^{1/2}$$

Shear velocity

$$v_s = 1.1 \times 10^8 \mathrm{cm/s} \left(\frac{\rho}{10^{14}\mathrm{g/cm}^3}\right)^{1/6} \left(\frac{Z}{38}\right) \left(\frac{302}{A}\right)^{2/3} \left(\frac{1-X_n}{0.25}\right)^{2/3}$$

- Magnetic evolution leads to an unstable configuration in the core ⇒ MHD instabilities with growth time $\approx R/v_A \approx 0.1$ s
- Magnetic stresses rupture the crust ⇒ release of elastic energy over a timescale $\approx \pi R/v_s \approx 0.3$ s
- Core and crust evolve smoothly, stresses are released in the magnetosphere via plasma instabilities/magnetic reconnection ⇒ very short timescale, < 0.01 s ($v_A \sim c$)

All three scenarios provide timescale in rough agreement with burst duration/rise time

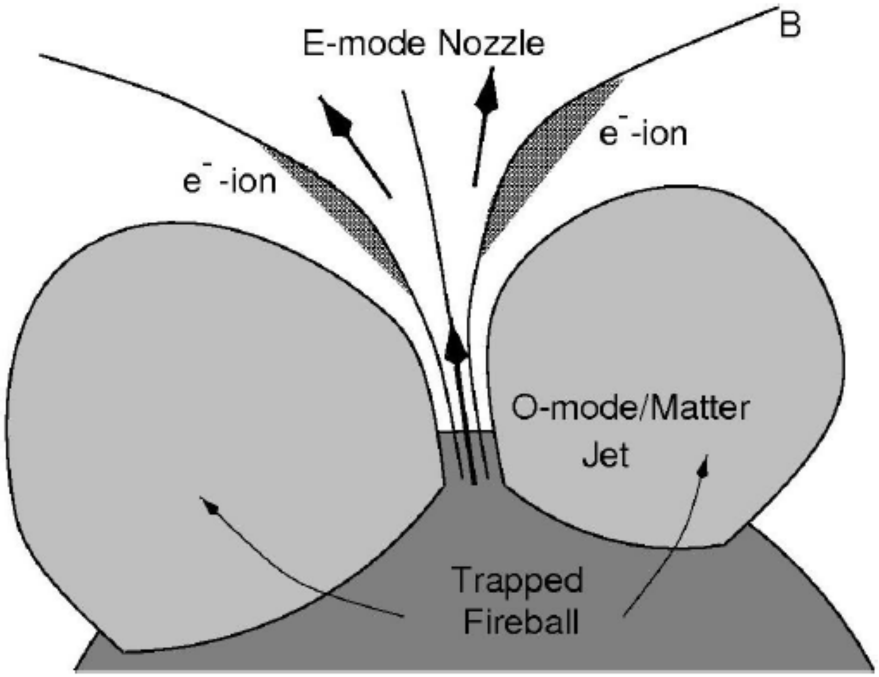
No serious problem with energetics (including giant flares)

Burst Emission

- Magnetic reconfiguration produces particle acceleration
- Electrons moving along the curved field lines emit γ-rays which drive a pair cascade
- The pair plasma is confined by the magnetic field if

$$B_{\rm dipole} > 2 \times 10^{14} \left(\frac{E_{\rm fireball}}{10^{44}\ {\rm erg}} \right)^{1/2} \left(\frac{\Delta R}{10\ {\rm km}} \right)^{-3/2} \left(\frac{1 + \Delta R/R}{2} \right)^{3}\ {\rm G}$$

- Confinement leads to an optically thick “fireball”
- Radiation escapes preferentially in the X-mode, due to the much reduced opacity



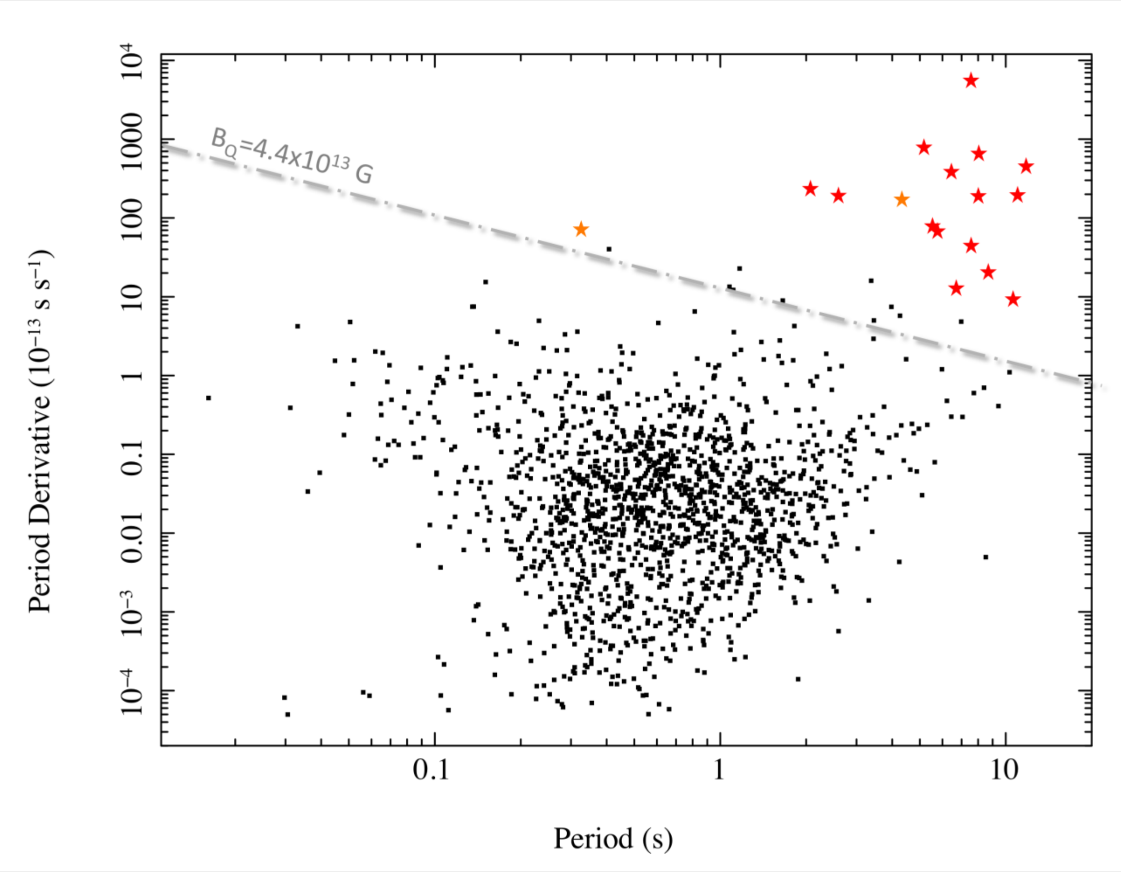
No detailed model for burst emission available as yet

SGRs/AXPs vs. High-B Pulsars

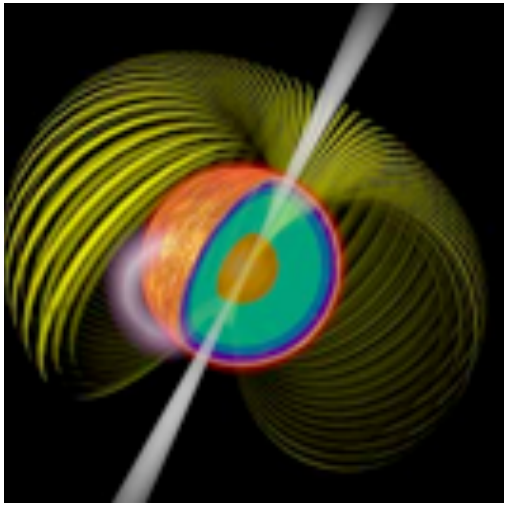
"Magnetar activity" (bursts, outbursts, …) for a long time detected only in high-B sources ($B_p > 5\times10^{13}$ G) : AXPs+SGRs (★) and PSR J1846-0258, PSR J1622-4950 (★)

The ATNF Catalogue lists 20 PSRs with $B_p > 5\times10^{13}$ G (HBPSRs)

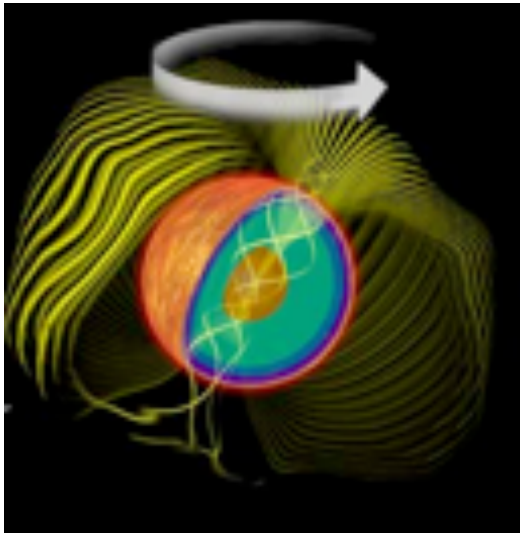
A high dipole field does not always make a magnetar, but a magnetar has necessary a high dipole field



- 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



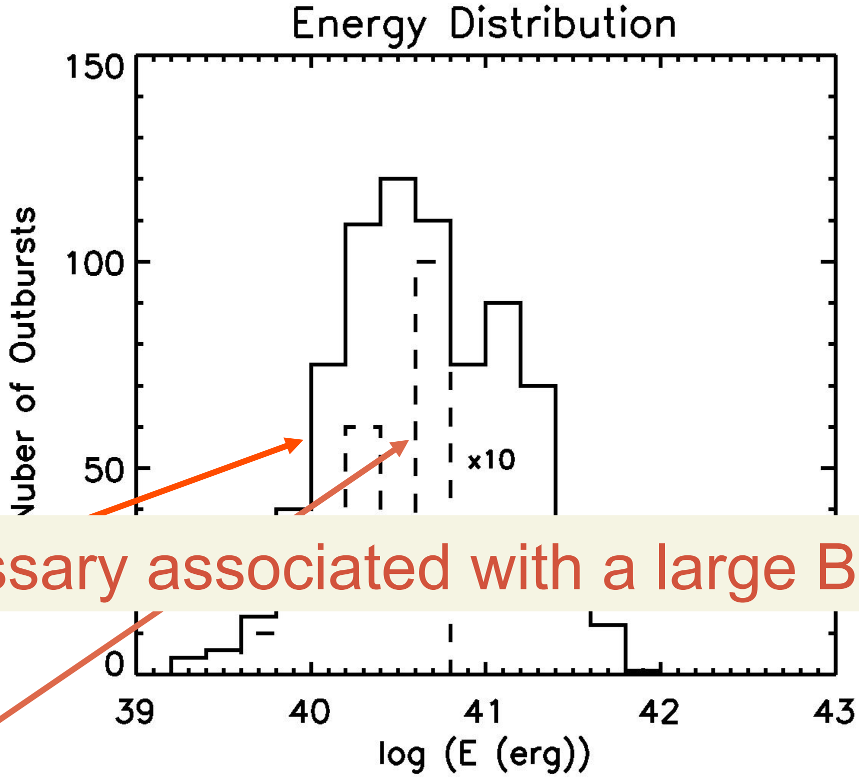
High-B PSR



SGR/AXP

Calculation of magnetic stresses acting on the NS crust at different ages (Perna & Pons 2011; Pons & Perna 2011)

Activity strongly enhanced when $B_{tor,0} > B_{p,0}$



A large B_{tor} is necessary associated with a large B_p

$B_{tor,0}$
$B_{p,0} = 2.5x10^{14}$ G

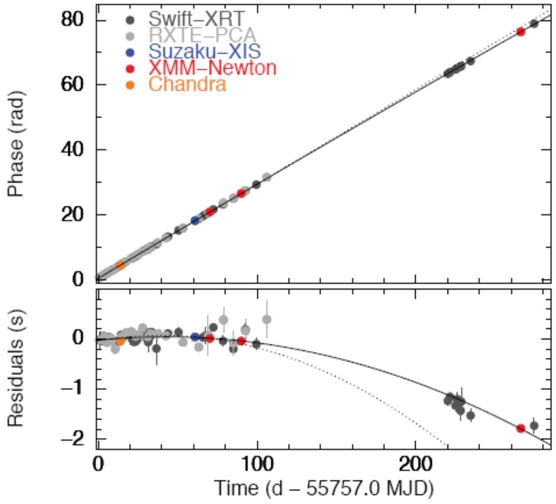
$B_{tor,0} = 8x10^{14}$ G
$B_{p,0} = 1.6x10^{14}$ G

The “Low-Field” Magnetars

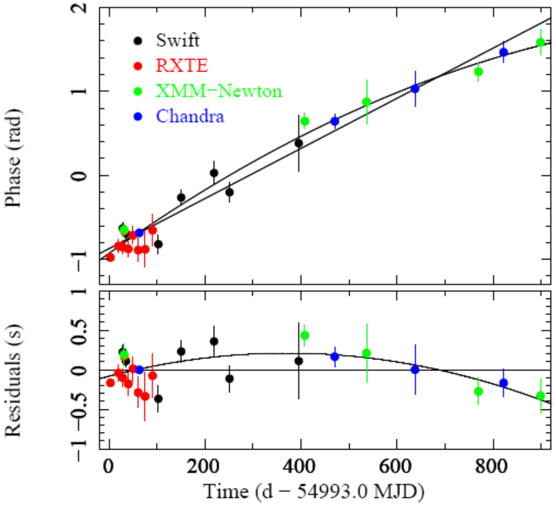
- Three peculiar magnetar candidates discovered since 2009: SGR 0418+5729 (van der Horst et al. 2010, Esposito et al. 2010, Rea et al. 2010), Swift J1822.3−1606 (Rea et al. 2012, Scholz et al. 2012) and 3XMM J1852+0033 (Rea et al. 2014)
- All the features of a (transient) magnetar
  - Rapid, large flux increase and decay
  - Emission of bursts
  - Periods in the range ≈ 8-11 s

Hunting for $\dot{P}$

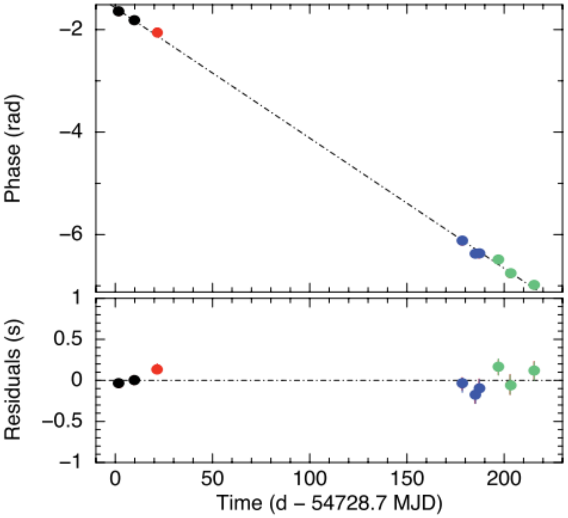
Swift J1822 (Rea et al. 2012)



SGR 0418 (Rea et al. 2013)



3XMM J1852 (Rea et al. 2014)

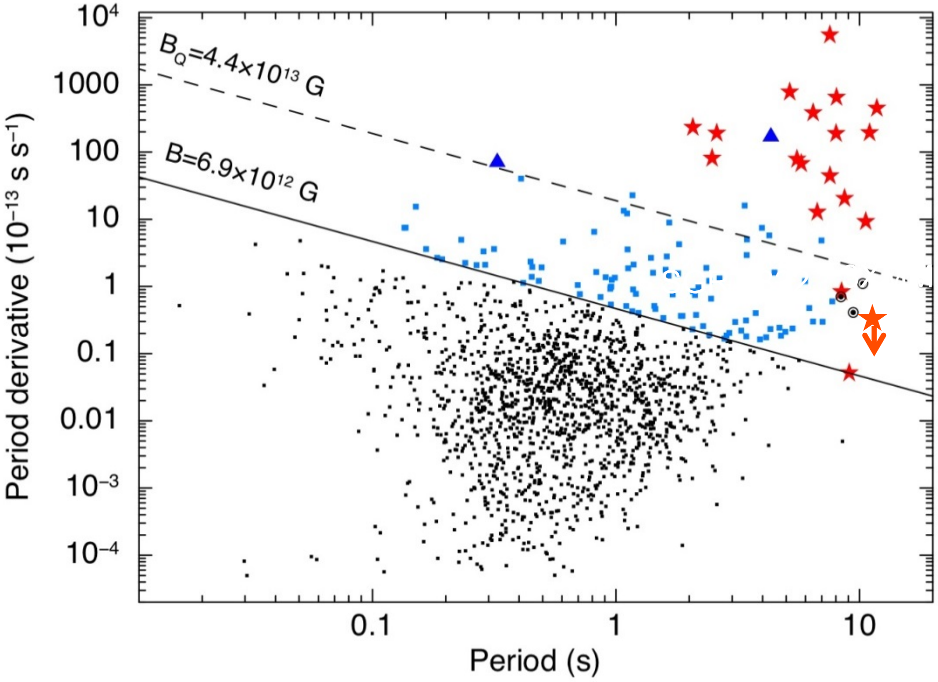


$\dot{P} = 8.3\text{x}10^{-14}$ s/s
$B_p = 2.7\text{x}10^{13}$ G
$\tau_c = 1.6$ Myr

$\dot{P} = 5.14\text{x}10^{-15}$ s/s
$B_p = 6.9\text{x}10^{12}$ G
$\tau_c = 29.5$ Myr

$\dot{P} < 1.4\text{x}10^{-13}$ s/s
$B_p < 4.1\text{x}10^{13}$ G
$\tau_c > 0.1$ Myr

Dr Pulsar and Mr Magnetar



Three “active magnetars” with B-field well within PSR range

More than 20% of known PSRs have B_p stronger than SGR 0418

A continuum of magnetar-like activity across the P-$\dot{P}$ diagram

A supercritical B_p not required to make a magnetar !

Neutron Star Evolution

- Rotational evolution

$$I\Omega\dot{\Omega} = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

- Thermal evolution

$$\frac{dE_{th}}{dt} = c_v \frac{dT}{dt} = -L_\nu - L_\gamma$$

Neutrino luminosity

Photon luminosity

- Magnetic evolution

$$\frac{\partial B}{\partial t} = -\nabla\times\left\{\eta\nabla\times B + \frac{c}{4\pi e n_e}(\nabla\times B)\times B\right\}$$

Ohm

Hall

Faraday induction equation

η is the magnetic diffusivity and strongly depends on T

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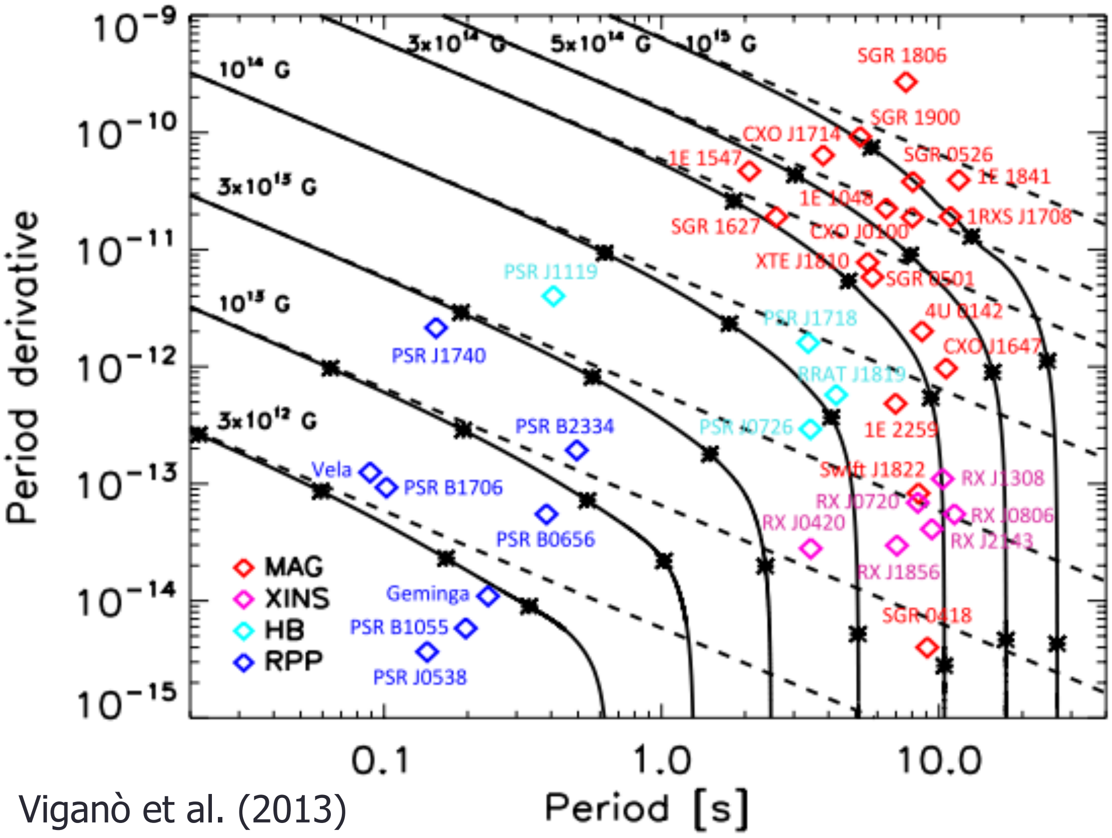
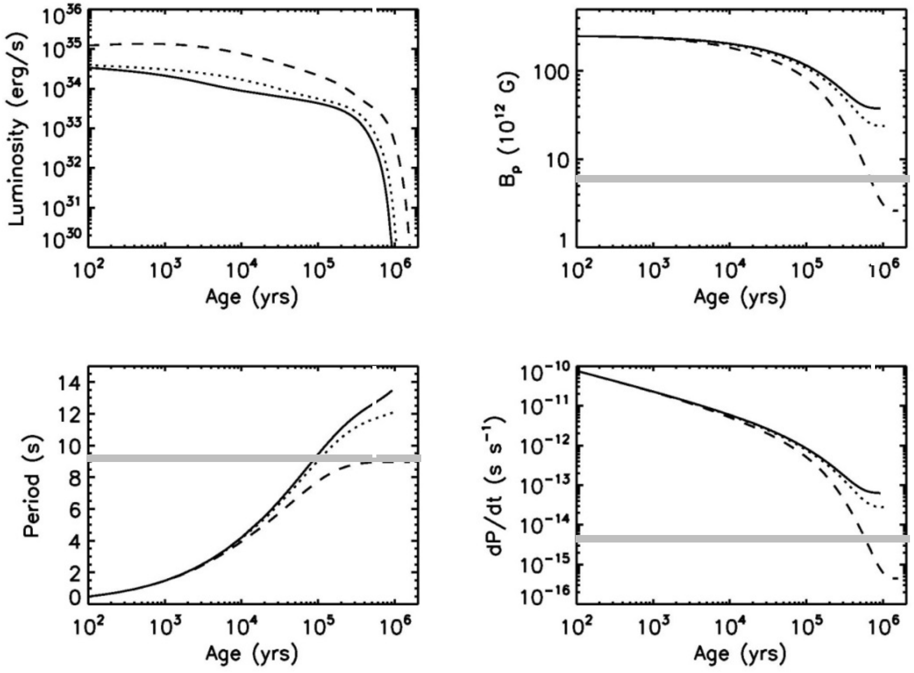


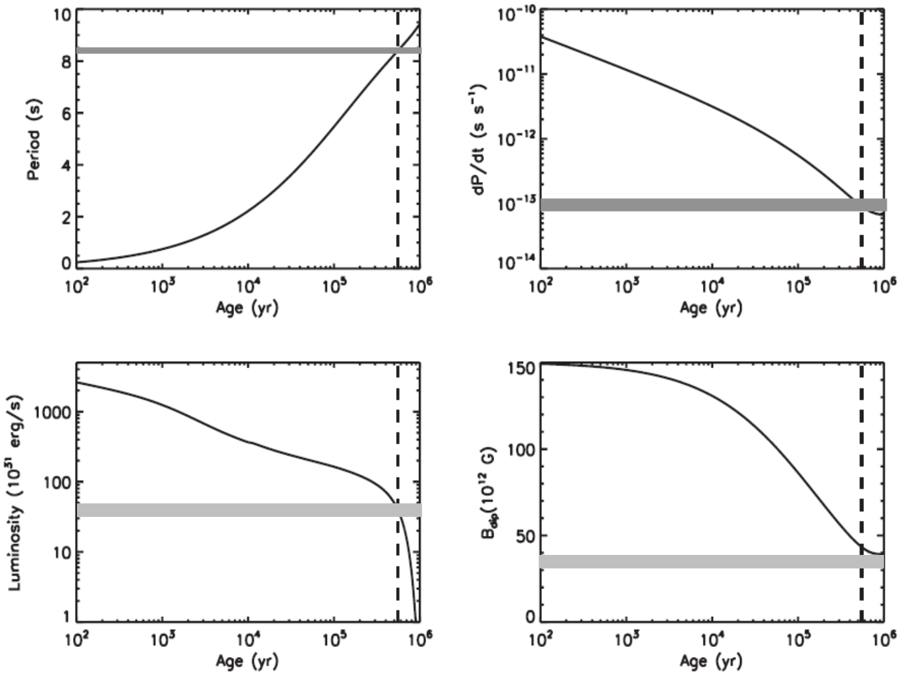
Viganò et al. (2013)

Are low-field sources old ?

SGR 0418 (Turolla et al. 2011)



SGR 1822 (Rea et al. 2012)



"Low-field" sources look indeed oldish (≈ 10^6 yr) magnetars in which the surface magnetic field substantially decaied

Wear and Tear

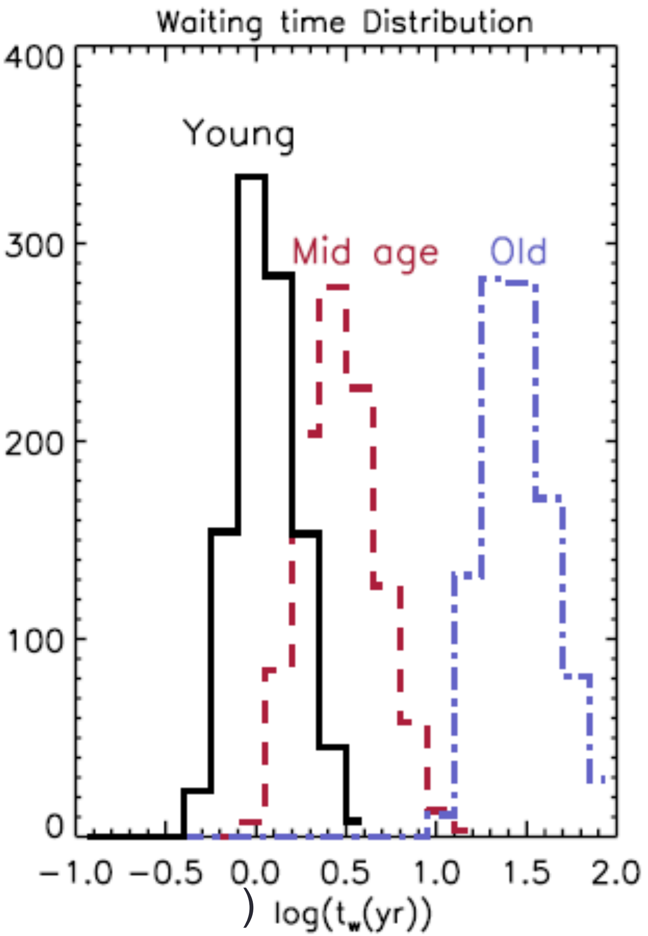
Crustal fractures possible also at late evolutionary phases (≈ 10^5 – 10^6 yr; Perna & Pons 2011)

Burst energetics decreases and recurrence time increases as the NS ages

For $B_{p,0} = 2 \times 10^{14}$ G and $B_{tor,0} = 10^{15}$ G,
$\Delta t \approx 10 - 100$ yr

Very close to what required for SGR 1822

Fiduciał model for SGR 0418 has similar $B_{p,0}$ and larger $B_{tor,0}$ ⇨ comparable (at least) bursting properties



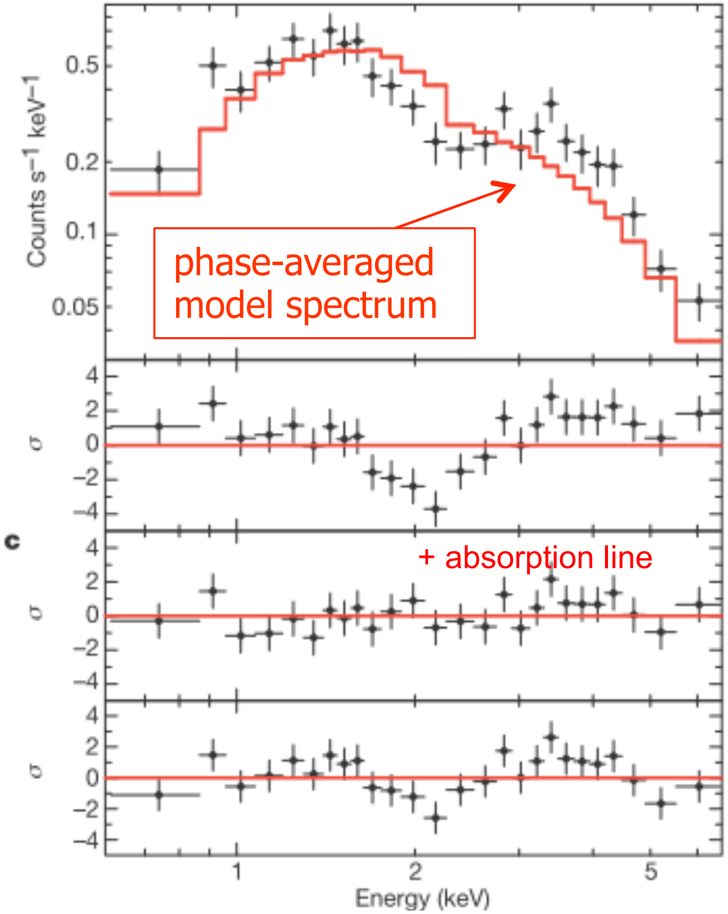
SGR 0418+5729: The “Surprise Egg”

SGR 0418 went in outburst on June 5, 2009. Subsequent monitoring with RXTE, Swift, Chandra and XMM (Esposito et al. 2010; Rea et al. 2010)

67-ks XMM observation on August 12, 2009 when the source was still quite bright

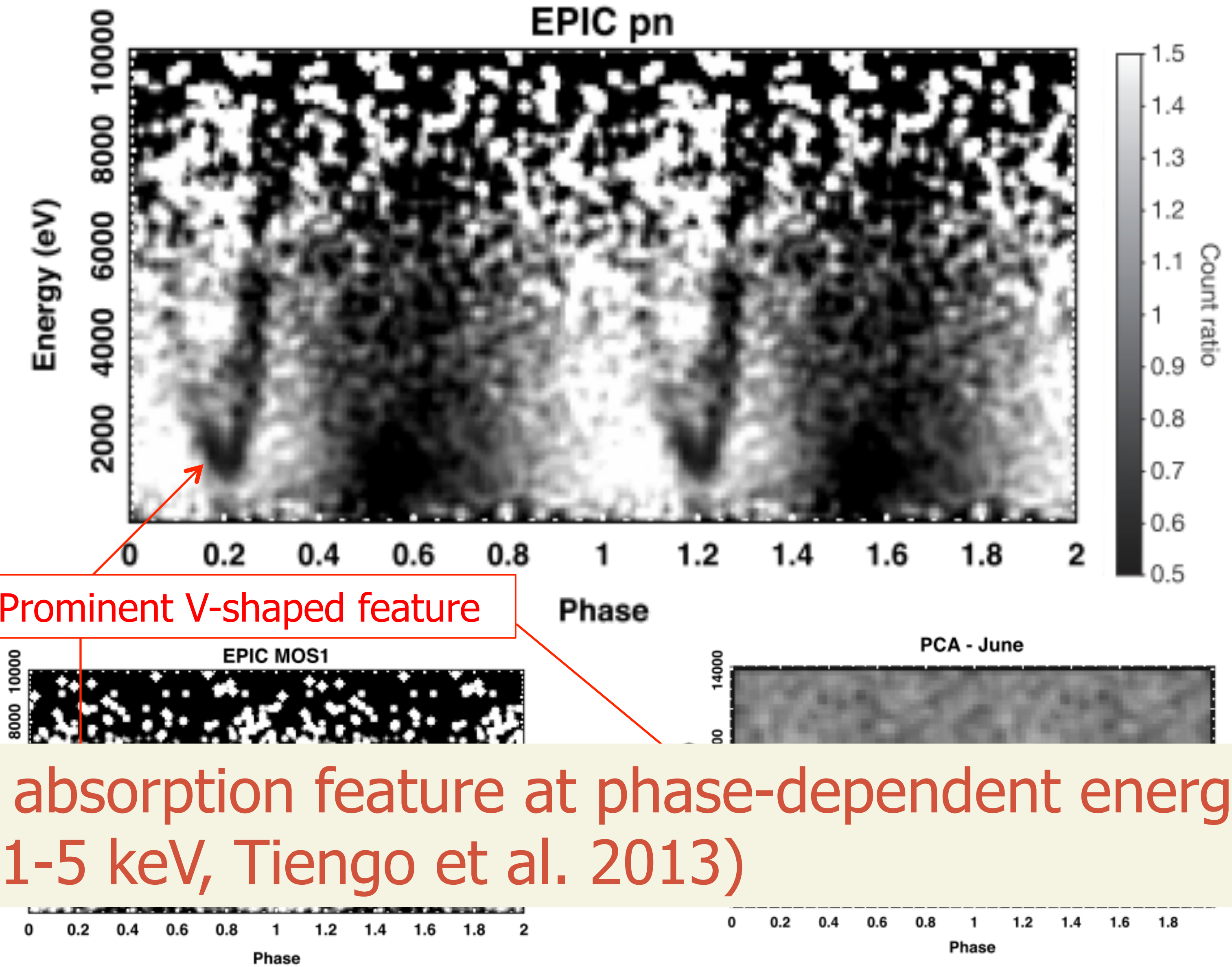
Phase-averaged spectrum is BB+BB or BB+PL: $kT_h \sim 0.91$ keV, $R_h \sim 0.9$ km

Phase-resolved spectra well fitted by rescaling the phase-averaged one, but not around phases 0.1-0.3 (and 0.5-0.6)



XMM Epic pn phase-resolved spectrum of SGR 0418 (phase interval 0.15-0.17)

Normalized phase-energy images (independent on spectral modelling)



Prominent V-shaped feature

An absorption feature at phase-dependent energy (≈ 1-5 keV, Tiengo et al. 2013)

Inferences

Most probably a cyclotron line (atomic transitions in H/He be

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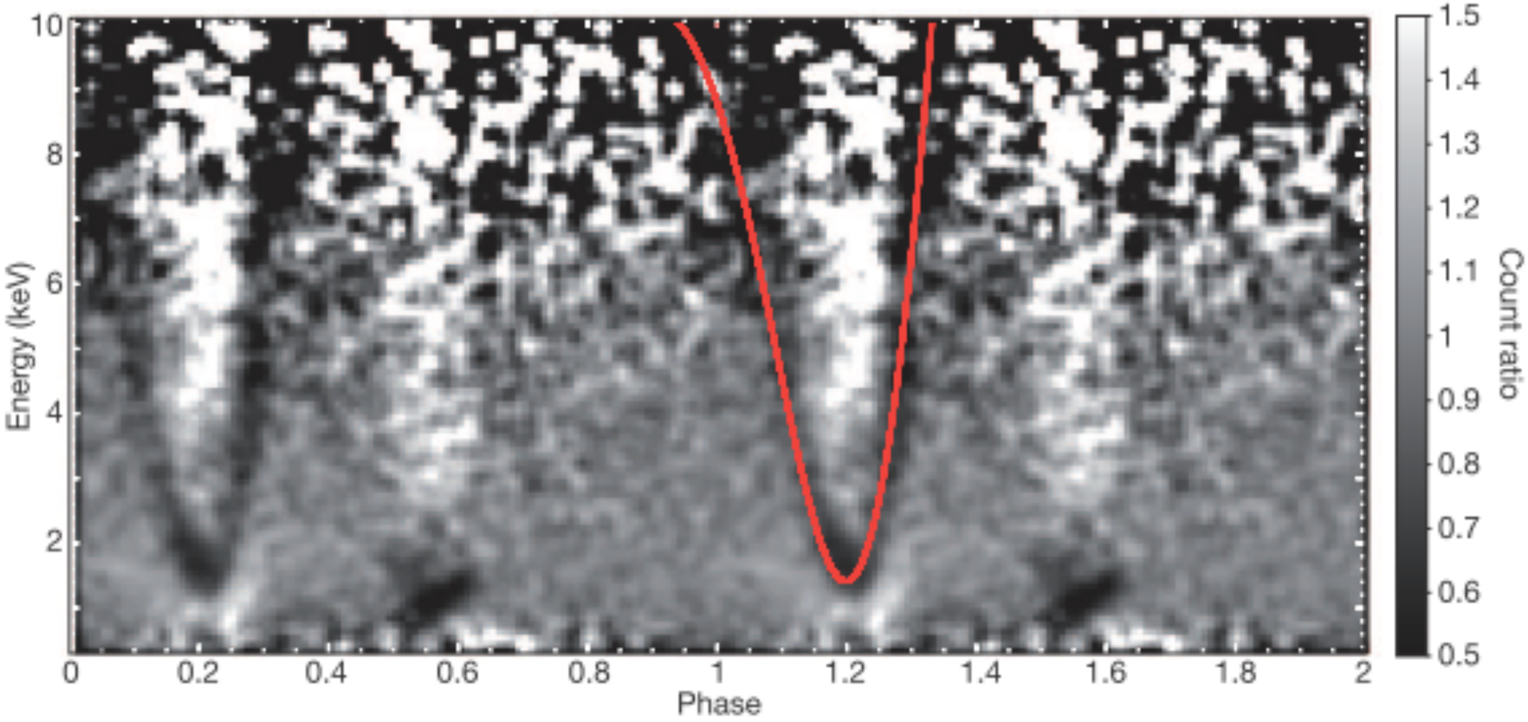
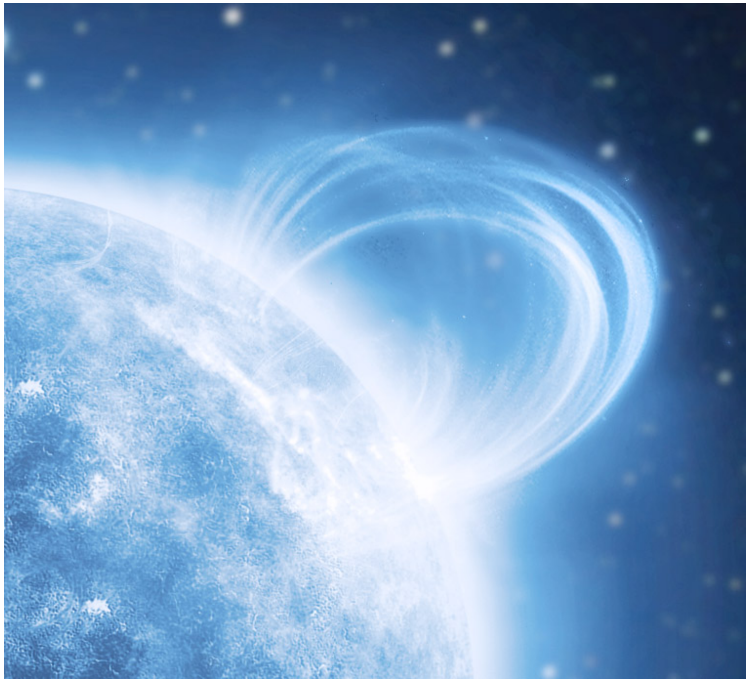


First direct measure of the magnetic field at the surface of a magnetar, B ~ $2\times10^{14} - 10^{15}$ G



An artist impression of SGR 0418 with the ejected magnetic loop

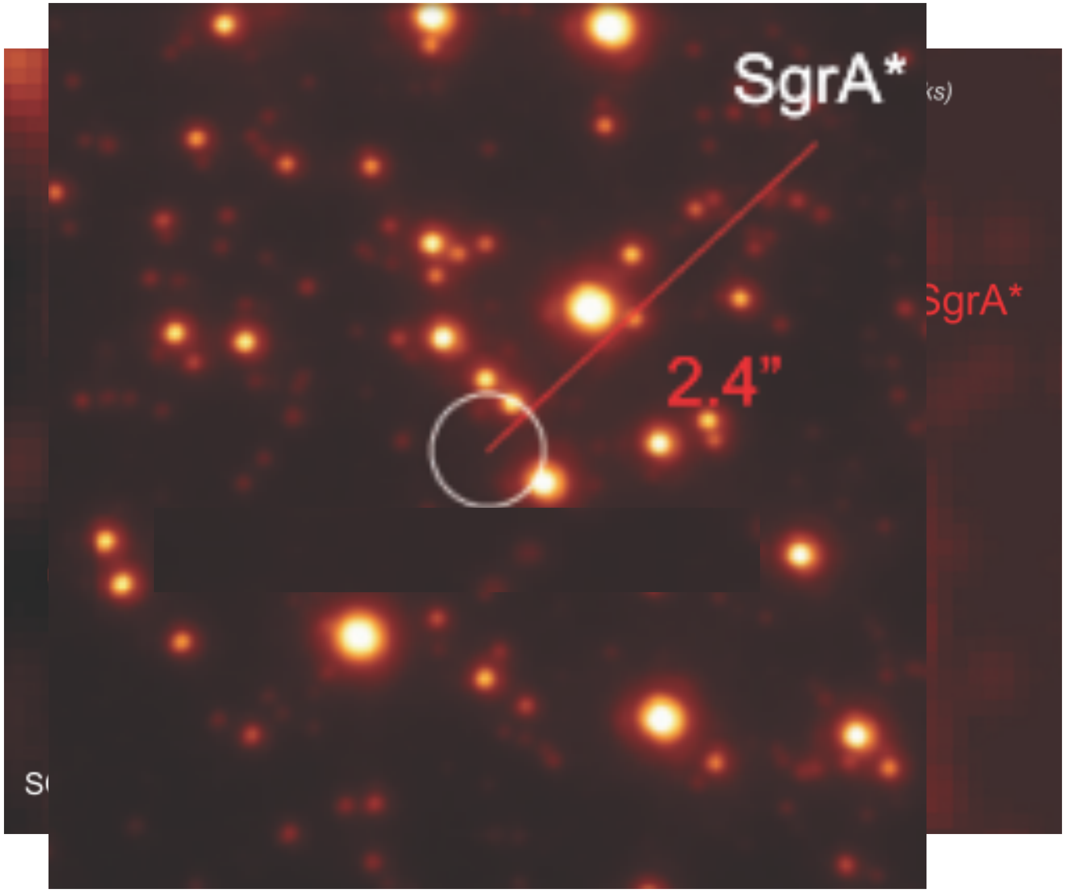
Of course, reality is a trifle more complicated…

A Space Oddity

The Galactic Center hosts the supermassive black hole Sgr A^* and a cluster of young, massive stars

Compact stellar remnants expected. Less expected was the presence of a magnetar at only 2.4" from Sgr A^*

SGR J1745-2900 was discovered on April 24, 2013 when it entered an outburst phase (Mori et al. 2013; Rea et al. 2013)



VLT/NaCo K_s image of the GC region

SGR J1745-2900

- Full-fledged magnetar: $P = 3.76$ s, $\dot{P} = 6.61\times10^{-12}$ s/s → $B_p \sim 1.6\times10^{14}$ G, $\tau_c \sim 9$ kyr
- Probability that it is a foreground/ background object ~ 10^{-6}
- Estimated distance to Sgr A^* ~ 0.1-2 pc
- Very likely (~ 90%) in a bound orbit around Sgr A^*

Future Developments

- Further support to the magnetar model: search for cyclotron line in other sources (preliminary results promising)
- Twisted magnetosphere model in general agreement with observations; hard vs soft power-laws
  - Nustar (and ASTRO-H)
  - More detailed modeling of magnetospheric currents
- Magnetar emission polarized: polarization measures key
- Only a general picture for the burst emission: need a quantitative model to compare with observations
- Extragalactic magnetars: relation with (long) GRBs ?
- The neutron star zoo: evolutionary links among different classes