Evolution of a strongly magnetized neutron star from its youth to old age.

José A. Pons
University of Alicante, Spain
In coll. with D. Viganò, N. Rea, U. Geppert, R. Perna, J.A. Miralles, R. Turolla

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- ✓Introduction/motivation.
- ✓Recent observations pose new problems.

- ✓The “standard” magneto-thermal evolutionary model.
- ✓Why B field affects temperature.
- ✓Why Temperature affects B field.

- ✓Observables: Cooling curves, CCOs, outburst phenomenology, “low B” magnetars

Why worrying about B field ?

- in "low field NSs" ($B<10^{12}$ G)

1D models are reasonably correct (anisotropy, if any, in the envelope)

The influence of magnetic field is probably not relevant (maybe in old NSs too cool to be observable).

- in "magnetars" ($B>10^{14}$ G)

Quite general agreement: they are "too hot for their age" and the magnetic energy is maintaining the high temperature and it is somehow responsible for the burst/flare phenomenology.

What happens to intermediate B objects (most of them !) ?

By the way, many of those are used to try to establish constraints on exotic matter: radius estimates, fast vs. Slow cooling processes …

New “magnetar puzzles” in the last decade

- Why do some objects display giant flares/outbursts, while others do not?
- How can be ``low-B magnetars'' (SGR 0418+5729 new Pdot implies B(dip) =6e12 G !, SWIFT J1822), if the magnetic field is their driving force ?
- What are CCOs ? Anti-magnetars or hidden magnetars ?

Multi-D magneto-thermal evolution of NSs just beginning to be considered, not yet in a fully consistent way.
Until recently only 1D cooling, and decoupled B-T evolution. In the past, multi-D results only for stationary solutions.

If we really want to say anything about properties of high density/exotic matter, or about evolutionary links between different objects, we must go beyond present NS evolution/cooling models. We see the surface ! not the interior. The information is coded through the outer layers (crust/envelope/atmosphere/magnetosphere).

Need to keep updating new advances in microphysics at ALL densities and perform realistic simulations with all possibly relevant physics.

(not always simple: superconductivity ?, magneto-elasticity ? Crustal fractures/starquakes ?).

Our final goal: study the evolution of a NS during its first Myrs of life considering the feedback between T and B evolution in the crust and core.

Magneto-thermal evolution of NSs

- Neutron star model (structure, EOS)
- Thermal evolution (energy balance equation): standard theory of cooling of Nss (e.g. St. Petersburg group and Dany Page works).
- Magnetic field evolution in the crust: Ohmic dissipation and Hall drift, Joule heating.
- Magnetic field evolution in the core: ambipolar diffusion ? buoyancy ? superconducting fluid dynamics, interaction between fluxoids and vortices ?
- Microphysics ingredients (thermal conductivity, electrical resistivity, neutrino emission processes, …) in presence of strong B
- Elastic/plastic properties of the crust: shear modulus, breaking strength (crust is much stronger than thought !). Necessary to understand starquake activity.
- Put everything in a numerical code. Results from simulations.

How does temperature affect the B field evolution ?

- B field evolution in NS cores ? Important, but its observational imprint is probably small.
- In a real NS, the crust is solid. It is appropriate to describe it as a Hall plasma, where ions have very restricted mobility and only electrons can move freely through the lattice.
- The proper equations are Hall MHD. If ions are strictly fixed in the lattice, the limit is known as EMHD (electron MHD)
- There are two basic wave modes: in the homogeneous limit (constant electron density), whistler or helicon waves, and also Hall drift waves in the inhomogeneous case.
- Transition from diffusive to hyperbolic regime depends on temperature.

Hall induction equation

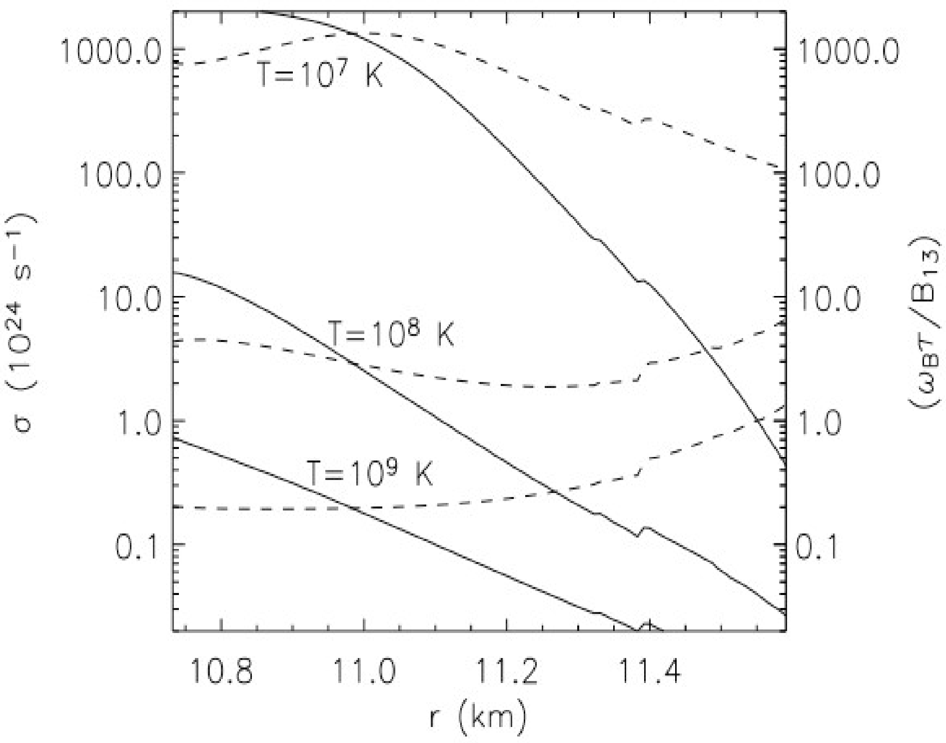
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left\{ \eta \nabla \times (e^{\nu} \boldsymbol{B}) + \frac{c}{4\pi e n_e} [\nabla \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} \right\}$$

Electrical resistivity strongly depends on T

How does temperature affect the B field evolution ?

Problems:

- Conductivity varies many orders of magnitude
- Magnetization parameter (magnetic Reynolds number) varies with time and can become very large (Hall term dominates)
- Back-of-the-envelope estimates (timescales, energy dissipation rate) varys in a range of 5-6 orders of magnitude



How does B field affect the thermal evolution ?

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

- Thermal evolution (energy balance equation): specific heat, thermal conductivity (anisotropy), neutrino emissivities.

  (Huge continuous effort Itoh, Yakovlev, Potekhin, Chabrier, Chugunov, Reddy … but some processes still need revision)
- Envelope and atmosphere models: boundary conditions DO matter (consistency ?).

  Plane parallel models are limited (purely horizontal field underestimates the surface temperature). Need to go multi-D.
- Magnetic field dissipation as a local heating source.

B field evolution: formation of current sheets.

- Diffusive (parabolic) terms.
- non-linear (Hall) terms (hyperbolic + higher order derivatives)
- Plus an “advective” term proportional to the conductivity gradient

• For purely toroidal fields and constant charge density

$$\frac{\partial B_\varphi}{\partial t} = -\frac{\hat{\tau}}{\hat{\sigma}} \boldsymbol{e}_\varphi \cdot \nabla \times [(\nabla \times \boldsymbol{B}_{\rm tor}) \times \boldsymbol{B}_{\rm tor}] = \frac{c}{4\pi e n_e} \frac{2B_\varphi}{R} \frac{\partial B_\varphi}{\partial z}$$

Burgers Eq (cylindrical coords.) !.

B field evolution: formation of current sheets.

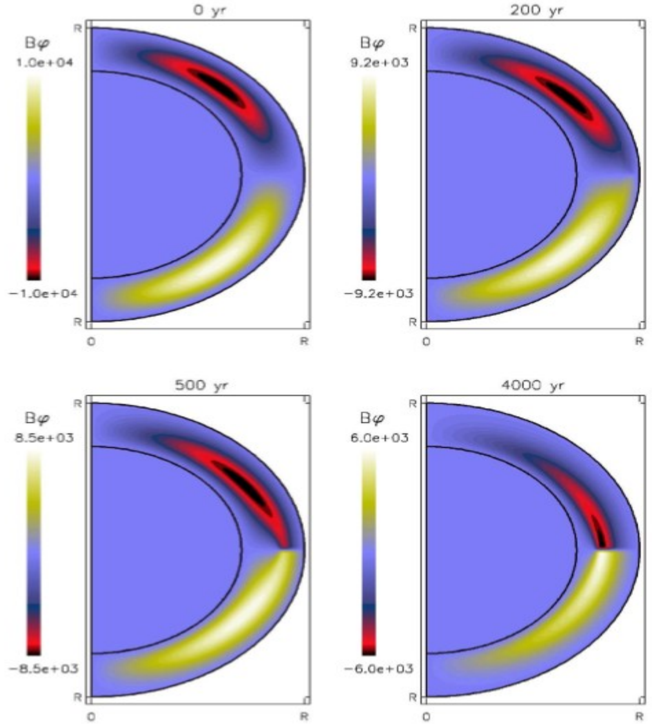
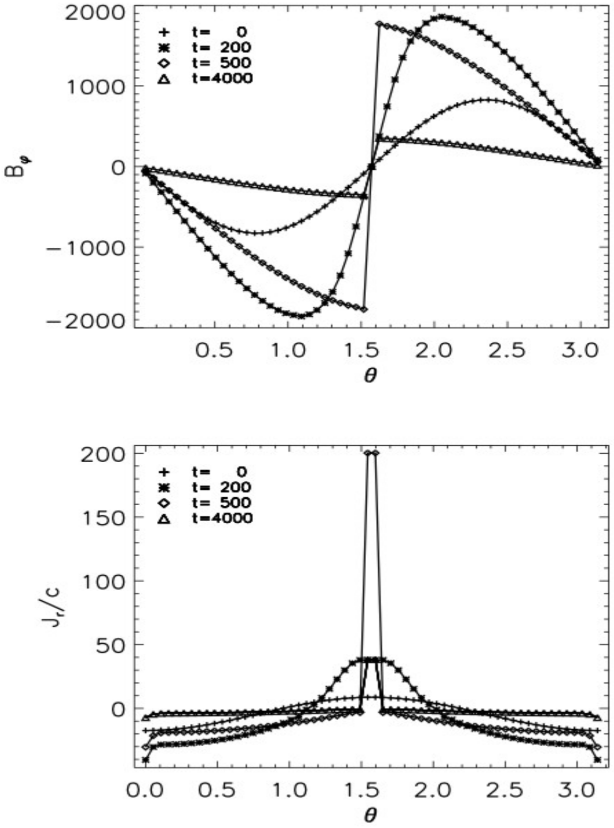
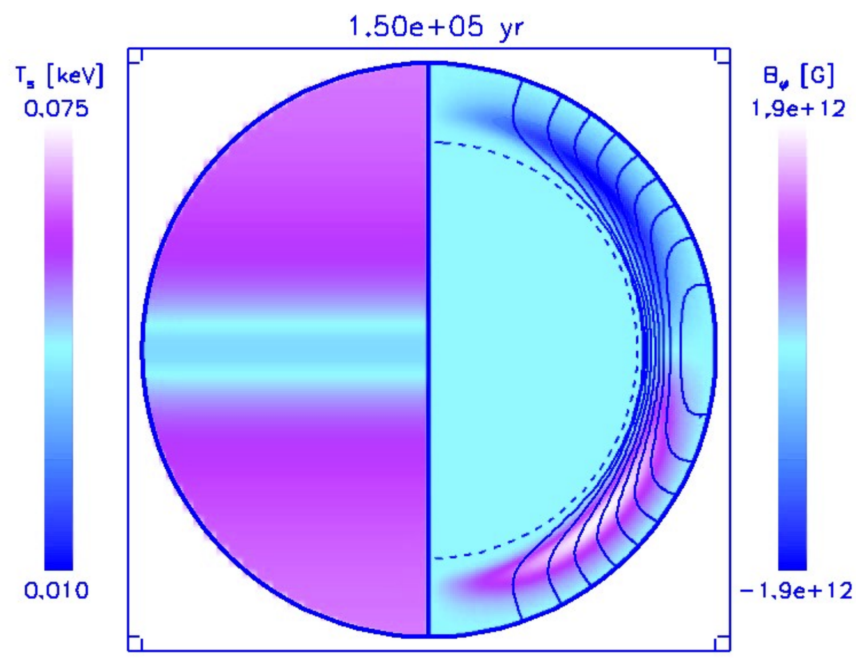


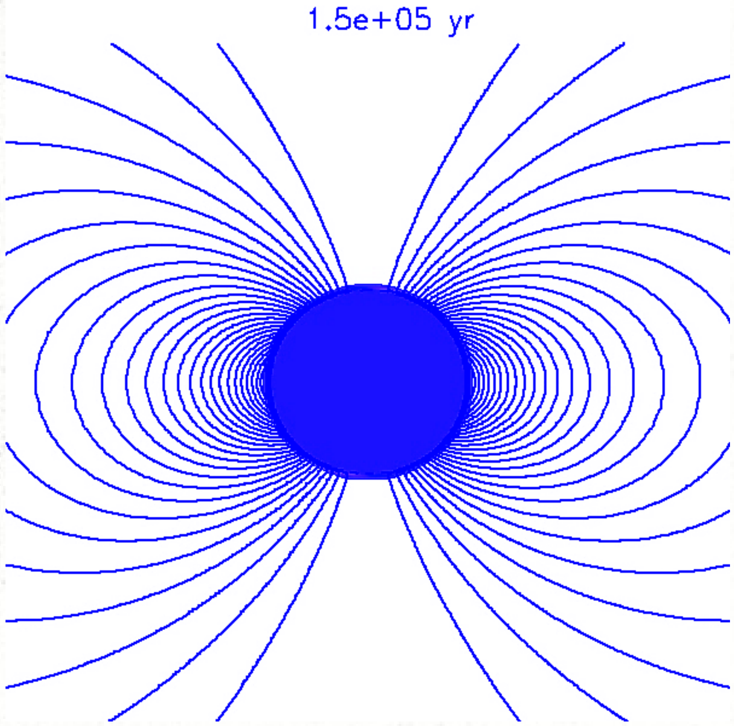
Figure 9: Evolution of a quadrupolar toroidal magnetic field confined into the neutron star crust. We show snapshots at $t = 0, 200, 500,$ and 4000 yr. The color scale indicates the toroidal field strength, in units of 10^{12} G. In the figure, the thickness of the crust has been stretched by a factor of 4 for clarity.



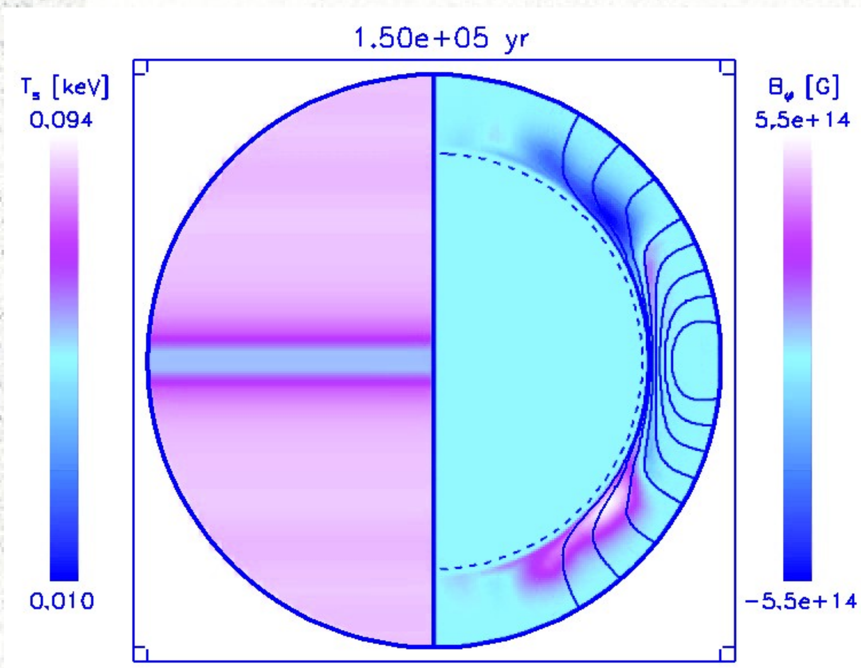
Viganò, Pons & Miralles (2012)

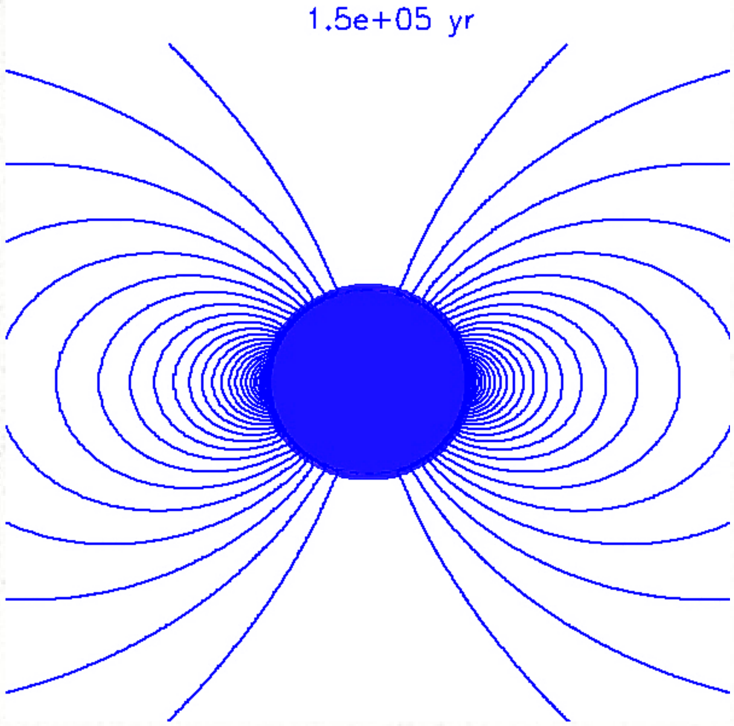
B field evolution: weak field



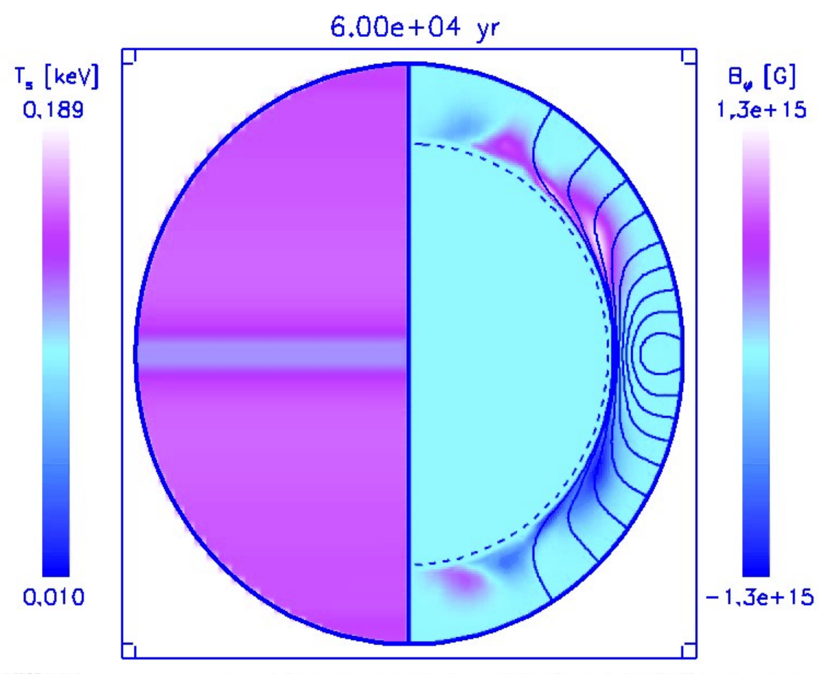


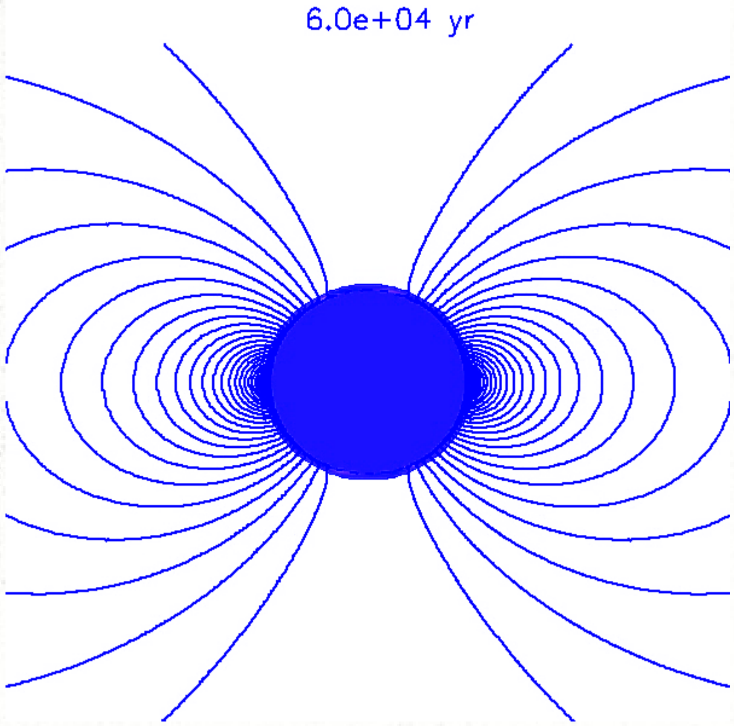
B field evolution: intermediate field



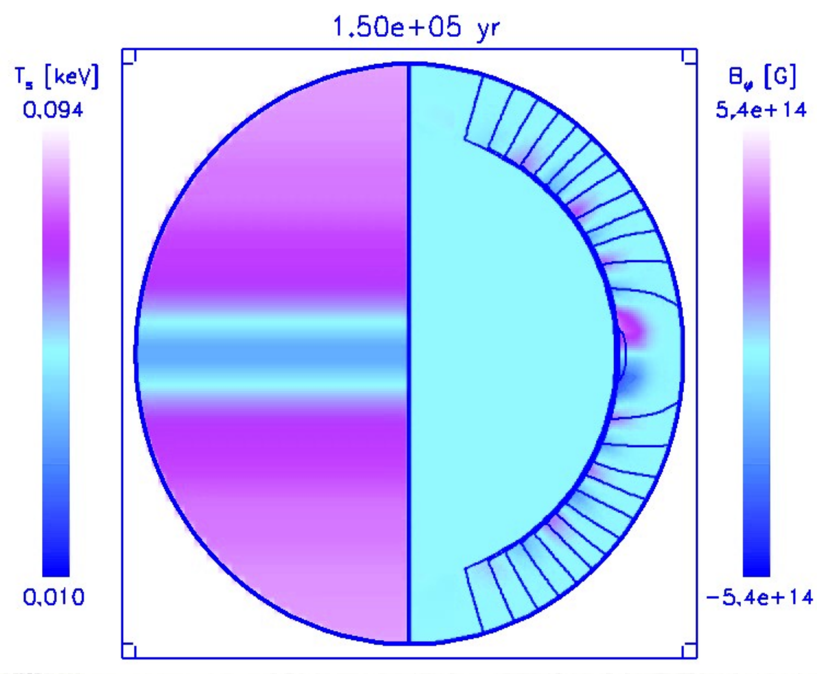


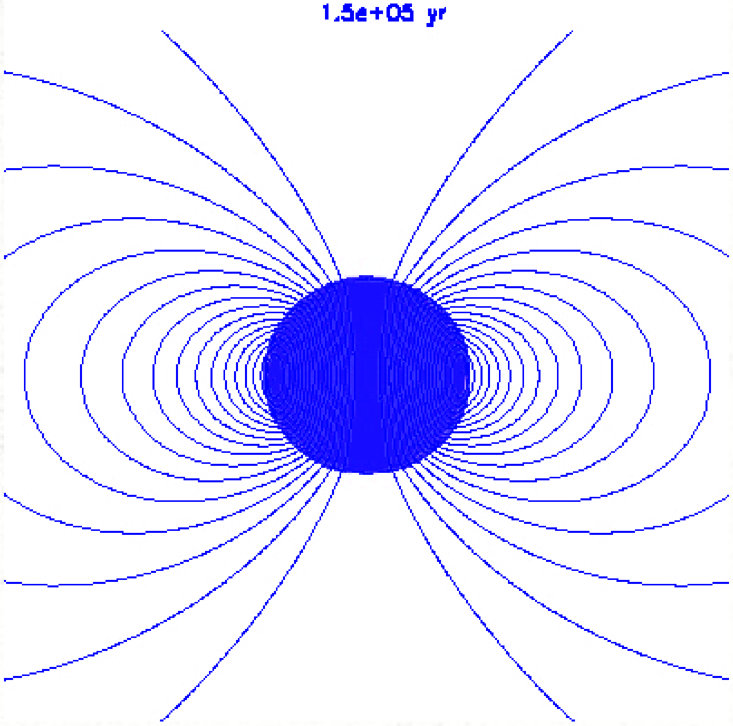
B field evolution: strong field



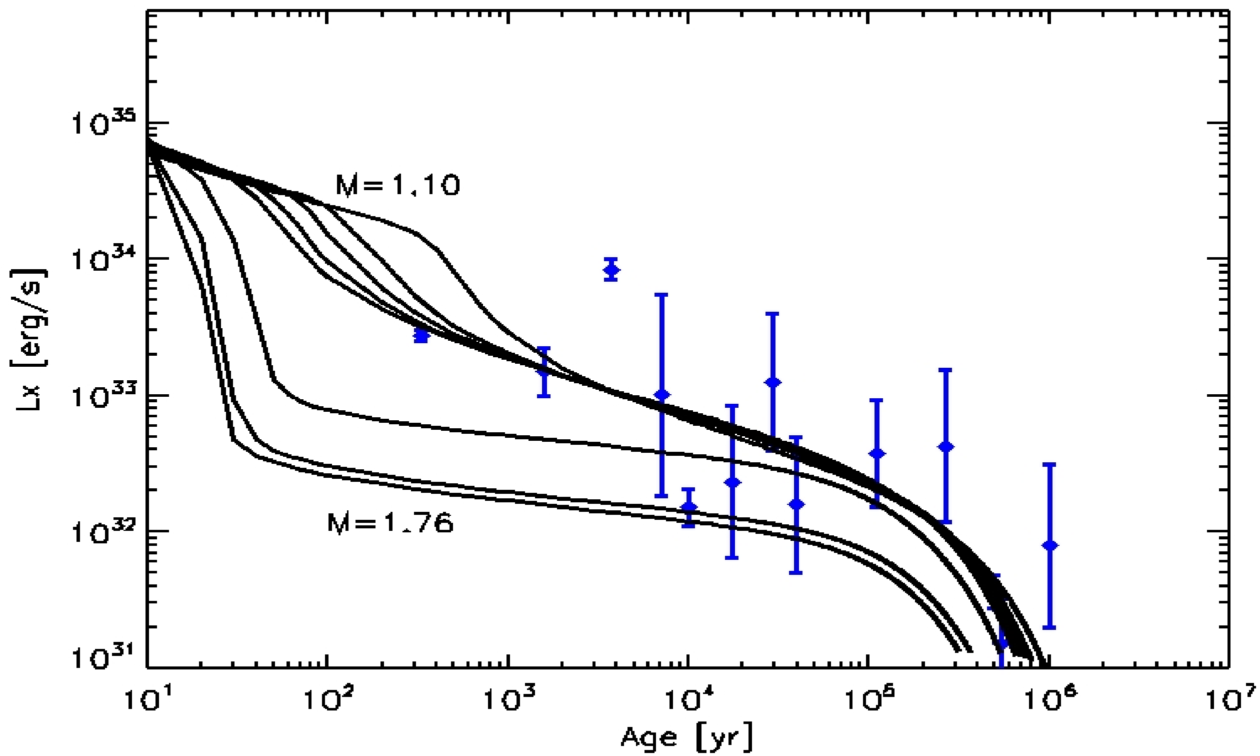


B field evolution: core field





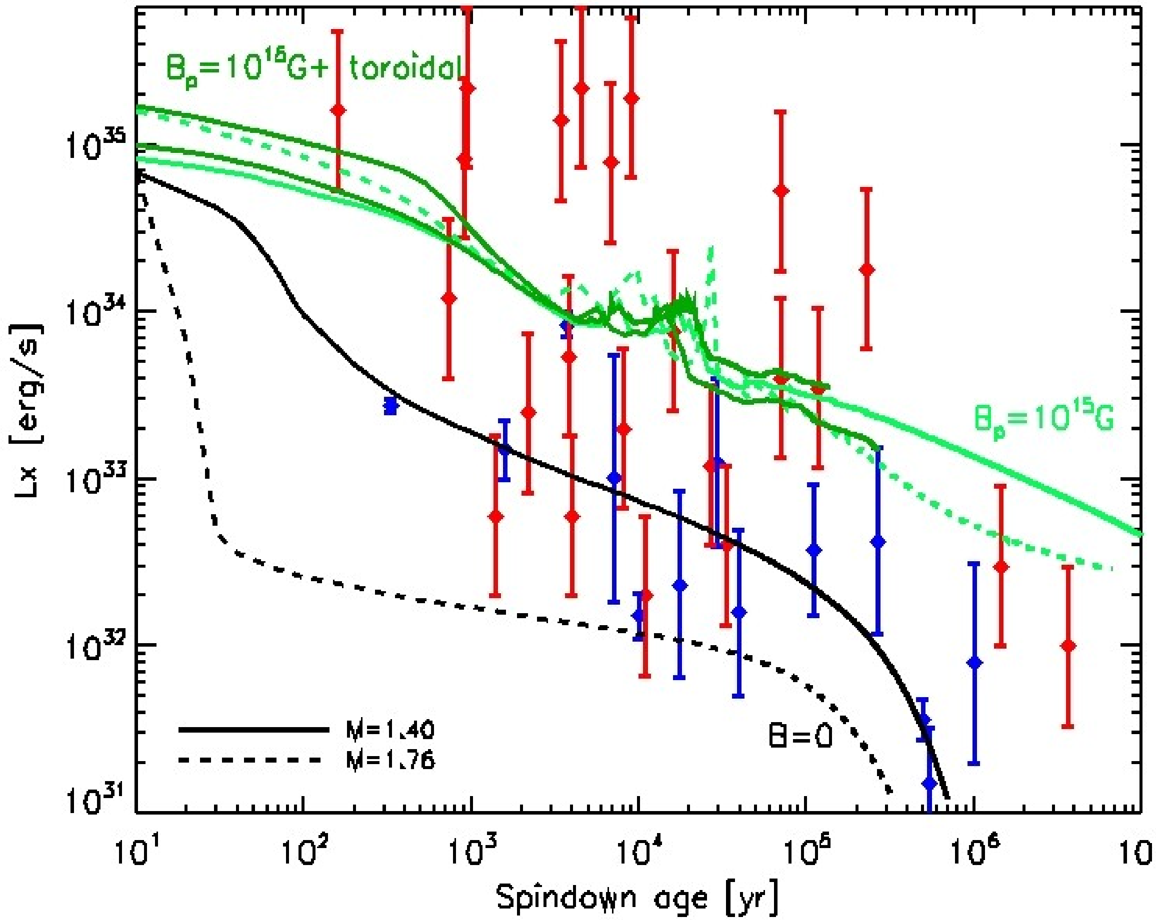
Cooling of low B neutron stars



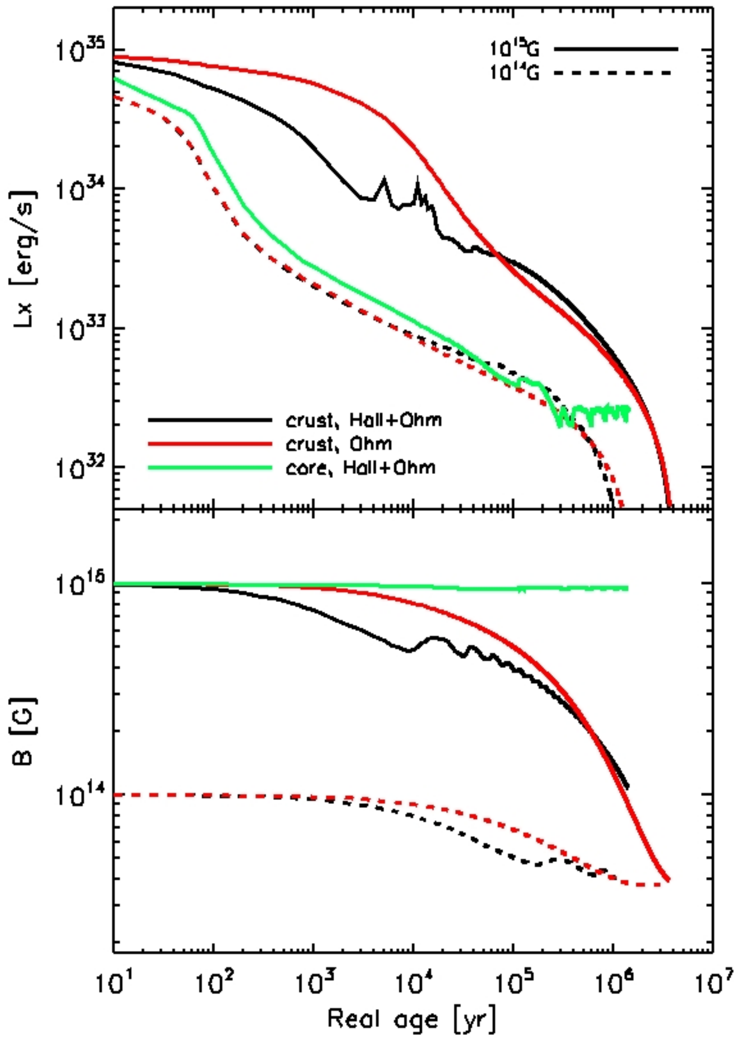
Note real age<spindown age. Everything fine
Except Vela (fast cooling) and (?) Puppis A.

Cooling of high B NSs:

higher luminosities, less sensitive to internal physics



Cooling: Influence of the Hall term



Lower luminosity (!) at intermediate ages, because of the faster reallocation of corrents towards the inner crust.

Compared to the purely resistive case, the field appears to be dissipated faster, but at late times it partially "reemerges" and shows oscillations.

Note late time convergence of dipolar component to few 10^{13} G

An old $B>10^{14}$ G rules out "crustal" fields, but we haven't seen any ....

Summary: Cooling of high B Neutron Stars

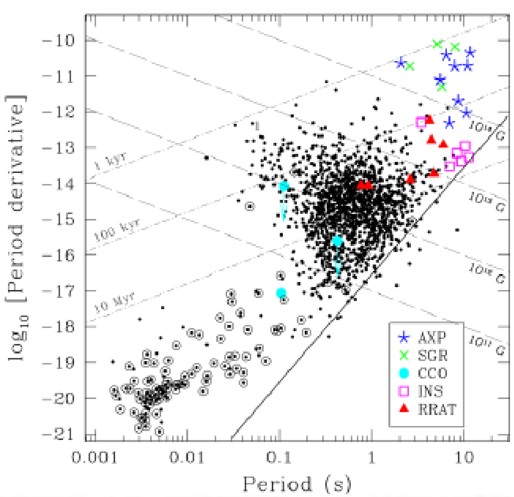
- Effects become very important for B >2-3 10^{14} G.
- Strong anisotropy in surface T distribution mapping the B field geometry.
- Higher luminosity (one order of magnitude or more)
- Differences due to NS masses or slow/fast cooling significantly reduced.
- If Hall term properly included, less impact than predicted, and convergence of models at late times.
- Still a couple of objects apparently too hot (H envelopes? atmospheres/color factor ?)
- Some microphysical inputs need revision.

CCOs: antimagnetars or hidden magnetars ?

CCO	SNR	age [kyr]	d [kpc]	P [ms]	$\dot{P}$ [10^{-17} s/s]	f_p %	B_p [10^{11} G]	B_s^{line} [10^{11} G]	L_{bol} [10^{33} erg/s]
CXOU J185238.6+004020	Kes 79	5.4-7.5	7.1	105	0.87	64	0.61	-	3.0-5.3
1E 1207.45209	G296.5+10.0	3-21	1.3-3.9	424	2.7-13	9	2.1-4.7	0.7-0.8	0.2-20
RX J0822.0-4300	Puppis A	3.3-4.1	2.2	112	< 20	11	< 3	0.8-0.9	5-10
CXOU J232327.9+584842	Cas A	0.33	3.4	-	-	-	-	-	6-8
CXOU J085201.4-461753	Vela Jr	0.7-1.3	1-3	-	-	-	-	-	0.2-0.7
CXOU J160103.1-513353	G330.2+1.0	3-10	5-10	-	-	-	-	-	1-6
1WGA J1713.4-3949	G347.3-0.5	1-10	1.3-6	-	-	-	-	-	0.6-15
XMMU J172054.5-372652	G350.1-0.3	0.9	4.5	-	-	-	-	-	~ 3.4
XMMU J173203.3-344518	G353.6-0.7	27	3.2	-	-	-	-	-	7.7-11
CXOU J181852.0-150213	G15.9+0.2	1-3	8-13	-	-	-	-	-	3-8

[Apadted and revised from de Luca 2008, Gotthelf & Halpern 2007-2011, Ho & Heinke 2009; and refs. within them]

[Kaspi 2010]



- Location close to the center of SNRs (like $\sim 60\%$ of < 20 kyr radio PSRs *[ATNF catalog]*)
- **No emission in radio/IR/optical, no Pulsar Wind Nebulae**
- **Very low spindown rates** $\Rightarrow$ **low inferred dipolar field** $B_p \lesssim 10^{11}$ **G**
- **X-ray: stable flux, thermal-dominated, with small hot blackbody component(s), or large pulsed fraction**

CCOs possibility I: antimagnetars

[Bonanno+ 2005,2006, Haplern & Gotthelf series]

Neutron stars born with slow rotation ($P_{in} \sim 0.1$ s) at birth.
$\Rightarrow$ inefficient dynamo action: low initial magnetic field

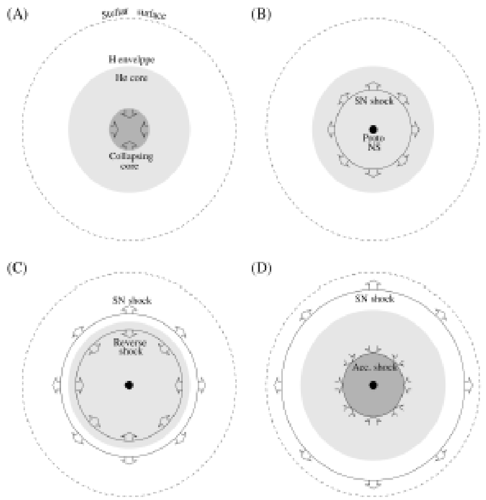
- Timing properties explained in a natural way: very slow evolution in $P - \dot{P}$ diagram
- P_{in} controls initial B and timing evolution

?

- Strong evidences for surface temperature anisotropies (small hot caps in spectra, large f_p)
- Luminosity is quite high
- $P - \dot{P}$ diagram: underpopulated region (pop. synthesis approach)

CCOs possibility II: hidden magnetars

Fallback onto Neutron Star from SN reverse shock



[image: Bernal+ 2010]

The fallback episode is highly hypercritical.

[Colgate 1971, Blondin 1986, Colpi+ 1996]

Duration: weeks to months.

Total accreted matter: $M_a \sim 10^{-4} - 10^{-1} M_\odot$.

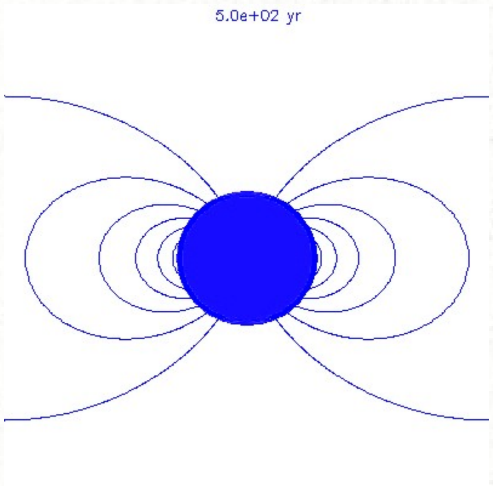
[Chevalier 1989]

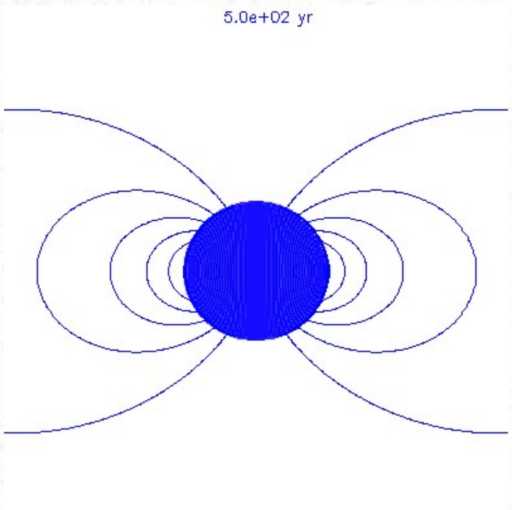
Hidden magnetic field scenario

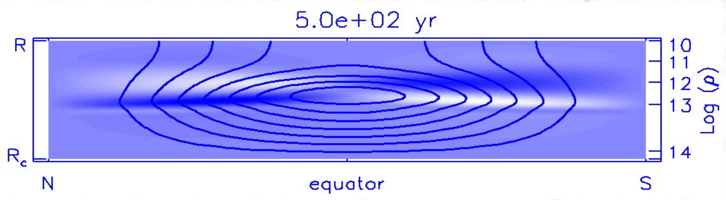
[Young & Chanmugam 1995; Muslimov & Page 1995; Geppert+ 1999; Ho 2011]

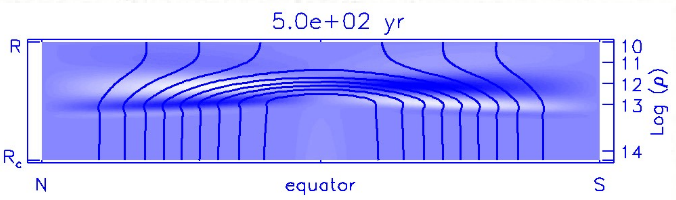
1. Neutron stars born with standard P_{in} and B_d.
2. Submergence of MF into inner crust.
3. The field slowly ($10^2 - 10^7$ yr) reemergences back to birth values (damped by Ohmic dissipation).

CCOs possibility II: hidden magnetars



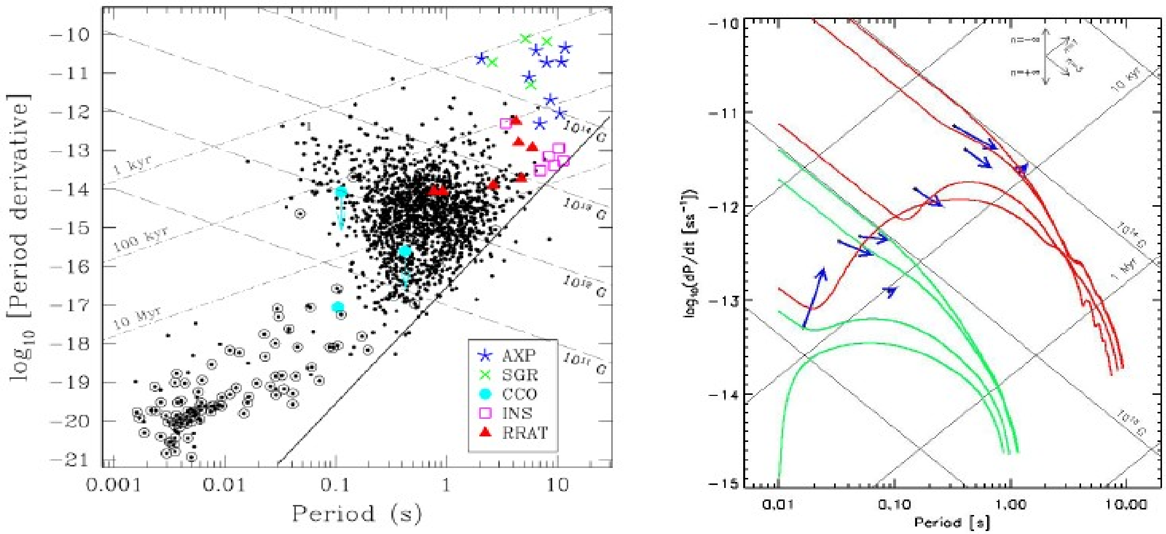






Viganò & Pons MNRAS 425 (2012)

CCOs possibility II: hidden magnetars



Tracks depend on accreted mass, natal MF, and initial period (if $M_a \gtrsim 10^{-4} M_\odot$)

- Links between CCOs and pulsars/magnetars.
- Young NSs with n<3 (Espinoza et al 2011) still in reemerence stage (Viganó & Pons 2012 MNRAS, Pons, Viganò & Geppert 2012, A&A in press).
- Look at T anisotropies and luminosity to distinguish between high/low B field objects.

Understanding the outburst phenomenology: Why small or large flux enhancement ?.

THE ASTROPHYSICAL JOURNAL LETTERS, 749:L1 (5pp), 2012 ??? PONS & REA

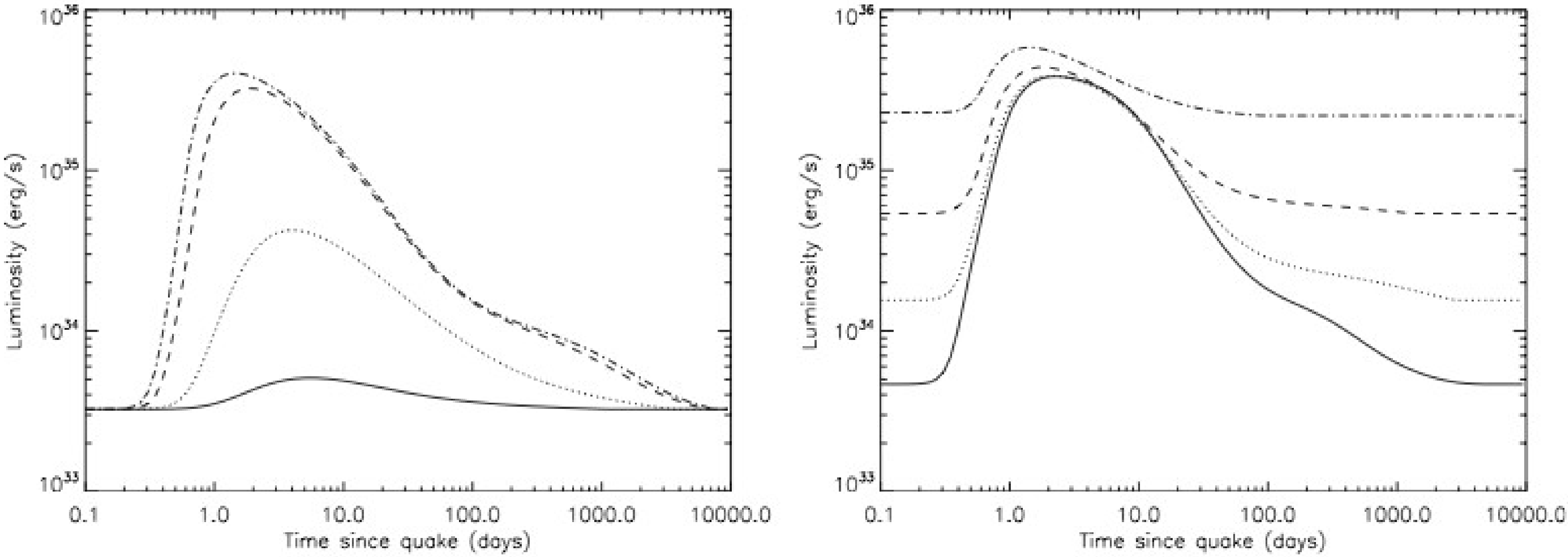


Figure 1. Luminosity vs. time after energy injection. Left panel: effect of the total energy injected. The models correspond to $E_{oc} = 1.7 \times 10^{41}$ erg (solid line), 1.7×10^{42} erg (dotted line), 1.7×10^{43} erg (dashed line), and 1.7×10^{44} erg (dash-dotted line). Right panel: comparison of models with the same energy injection ($E_{oc} = 1.7 \times 10^{44}$ erg) but varying the initial state (quiescent luminosity).

Pons & Rea 2012: neutrino processes limit luminosity !
The quiescence state determines the maximum
flux enhancement.

Understanding the outburst phenomenology: Why small or large flux enhancement ?.

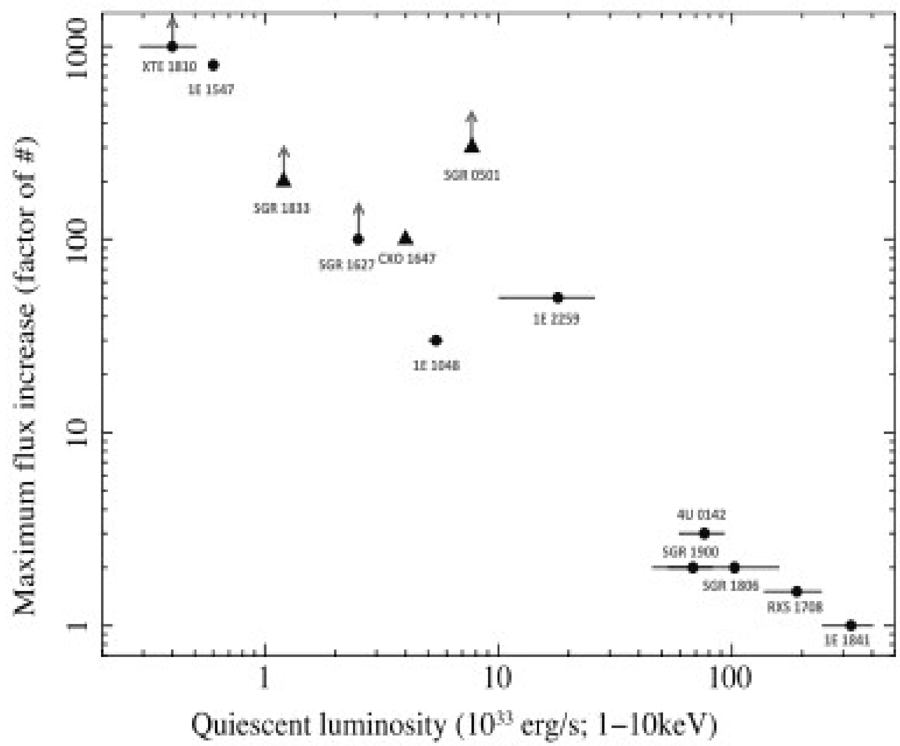


Figure 2. Quiescent luminosity vs. outburst maximum flux increase (all in the 1–10 keV band), for all magnetars showing bursts, glitches, or outbursts. Errors in the measurements include the uncertainties in the flux values and in the distances.

Pons & Rea 2012:
Correlation
betwen quiescence
Flux and flux increase.

Maximum flux at peak
similar for all cases
~1-2e35 erg/s !!

(not surprising, check
cooling curves
at t=0)

Understanding the outburst phenomenology : the quake model

In Equilibrium

$$M_{ij}^{\rm eq}(r,\theta) = \frac{B_i(r,\theta,t^{\rm eq})B_j(r,\theta,t^{\rm eq})}{4\pi} \sim \sigma_b(r,\theta,t^{\rm eq})$$

Magnetic field evolves in the crust (helicon waves, Hall waves) and dissipates. This changes the stresses balance.

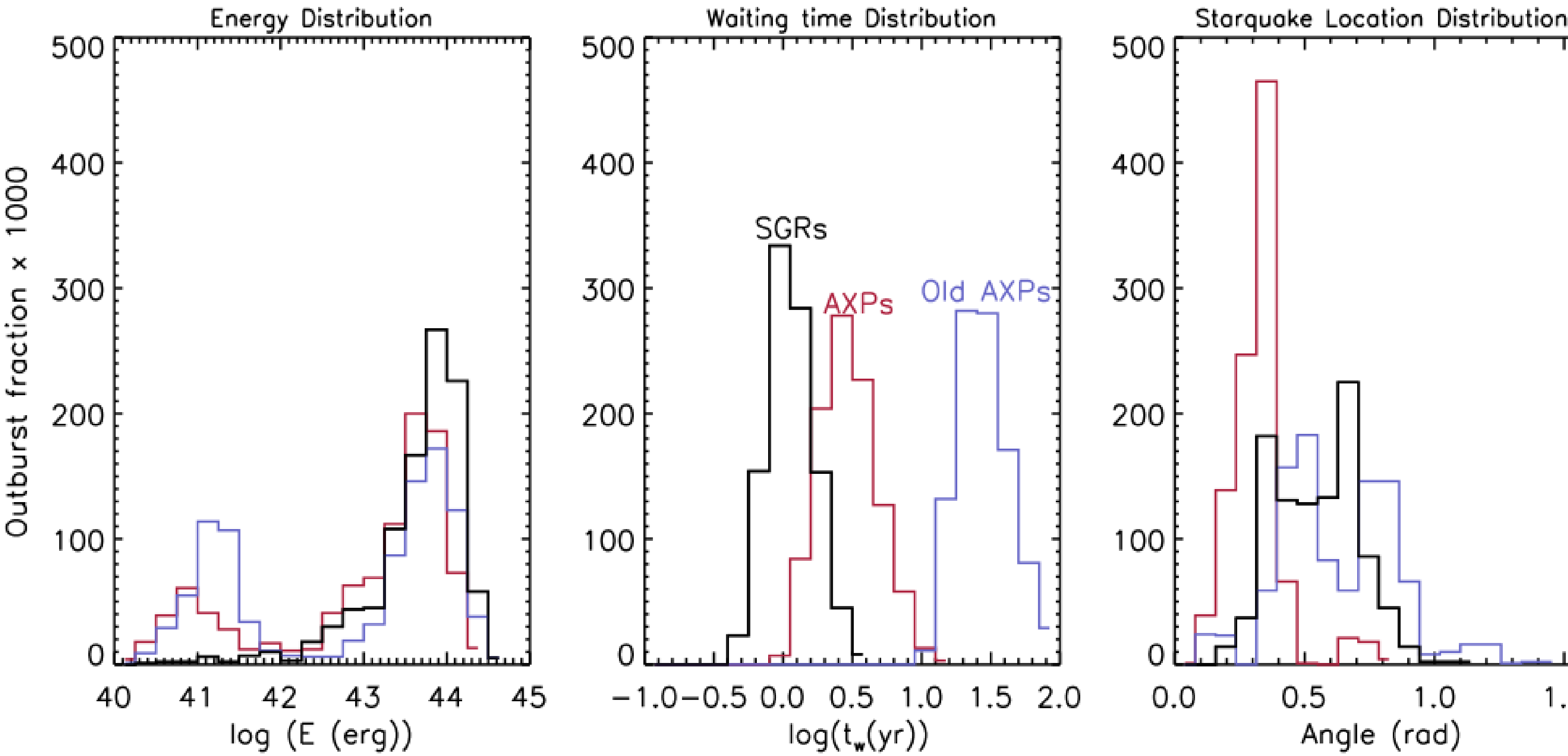
$$\sigma_b^{\rm max} = \left(0.0195 - \frac{1.27}{\Gamma - 71}\right) n_i \frac{Z^2 e^2}{a}$$

Chugunov & Horowitz (2010)

When the stress imbalance exceeds the shear breaking strength of the crust, the crust breaks, and elastic/magnetic energy is released and converted into electromagnetic energy.

See also the thermo-resistive instability (Price, Link, Epstein, Hui, 2011)

Understanding the outburst phenomenology: Different classes or simply aging effects ?

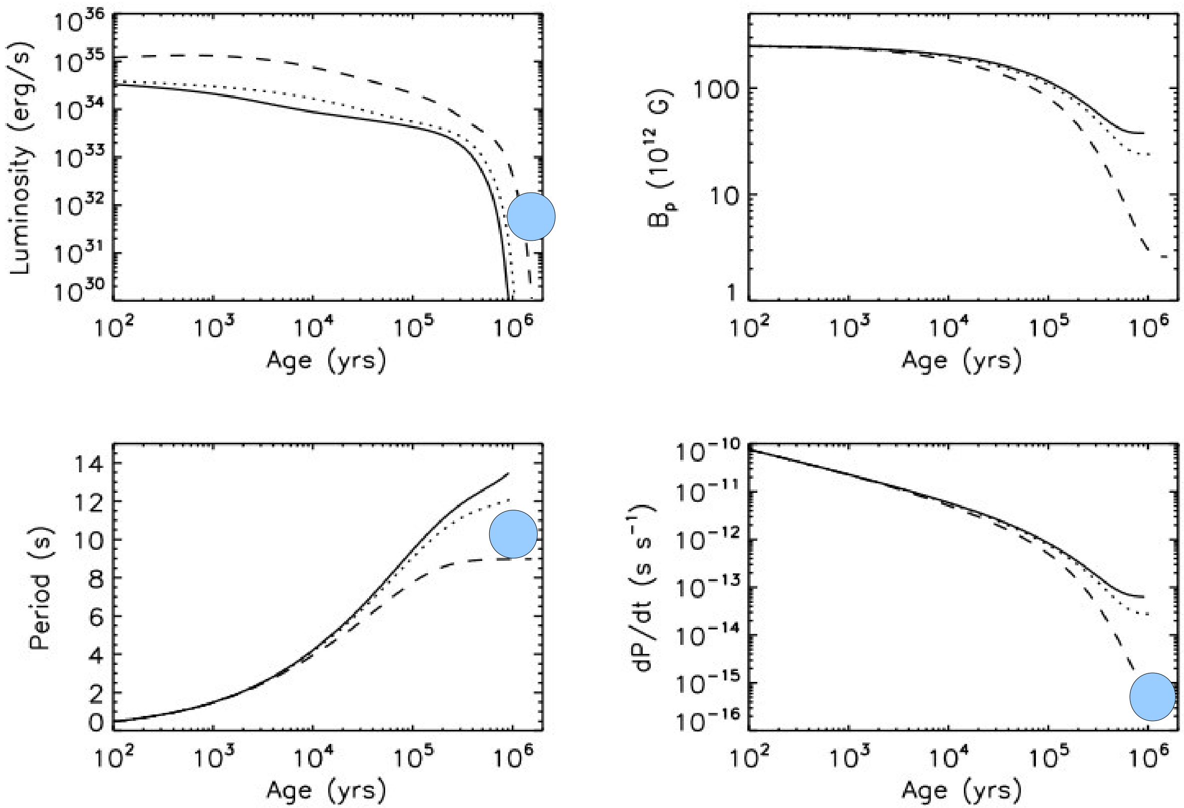


Outburst rates very dependent on age (Perna & Pons 2011)

Low field magnetars ?

- SGR0418+5729 (Rea et al. 2010, Science, 330, 944)
  - Large characteristic (not real) age (> 24 Myr !!)
  - Weak bursting activity (only 2 faint bursts)
  - Low dipole field B ~ 6×10^{12} G (in prep., unpublished)
- Main issues (discussed in Turolla et al. 2011)
  - P, $\dot{P}$ and B from magneto-rotational evolution
  - capacity of producing bursts
  - spectrum of the persistent emission

The case of SGR 0418+5729: an Old Magnetar ?



Both magneto-rotational history and spectral properties are consistent with the old magnetar picture. (Turolla et al. 2011, ApJ)

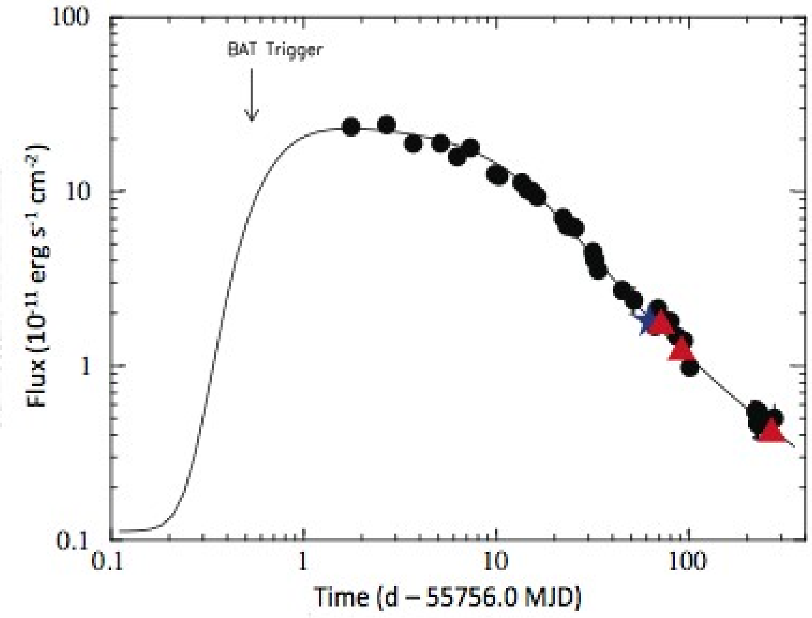
Low field magnetars

- SGR 1822-1606 (Rea et al. 2012)
  - Outburst
  - Relatively low dipole field ($B = 3\text{-}4 \times 10^{13}$ G)
  - P, $\dot{P}$ and B from magneto-rotational evolution
  - Post-outburst thermal relaxation !

SHORT TERM COOLING ALSO INTERESTING !

The case of SGR 1822-1606: a middle age outbursting magnetar ?

(The extrange case of Dr. Pulsar and Mr. Hyde-hidden magnetar)



Rea et al. 2012

Cooling curve consistent with a 0.5 Myr old born as magnetar ? (now B=5e13 G). 4×10^{25} erg/cm^3 injected in the outer crust (total energy ~10^{42} erg). Internal field still 10^{14} G.

Diagnosing internal physics with magnetar cooling !

Too good to be true … degenerate solutions ?.

Summary I: Childhood and teen agers (unstable/transient/active/look changes)

- The first *Hall stage* (few kyrs) is very active. Whistler and Hall waves stress the crust, resulting in frequent glitches and flares. A *timing anomaly* is always present, but only when the stresses break the crust or somehow helicity is transferred to the magnetosphere, fast magnetic reconnexion releases enough energy and there will be outbursts.
- Are CCOs antimagnetars or hidden high B NSs ? Hard to say from spin-down properties. The external dipole is NOT the internal field. Need to rely on spectral analysis and accurate luminosity measures to discern between models.
- Very important to handle correctly the formation of current sheets and strong, localized heat release.
- But Hall-induced fast dissipation is not that fast. Drift towards the interior where conductivity is high limits the expected effect. More ellaborated models show less variability and less dependency on initial conditions.

Summary II: Maturity

- After the Hall stage, the system reaches a quasi-equilibrium configuration (not simply dipolar) and the field has decayed about a factor of 10.

  Then, Ohmic dissipation dominates during 0.1 to 1 Myr.
- All NSs born as magnetars end up with similar fields. Look like isolated NSs or high field radio-PSRs. There is still a chance of rare transient phenomena (PSR J1846-0258, SGR 0418+5729, SGR 1822).
- Effect of B field large enough to hide fast cooling. Is rapid cooling going on in all NSs but we can only see it in some low field NSs ?

Summary III: Old ages

•When Joule heating is not efficient any more, the star cools down and dissipation proceeds much slower. Warning: A second Hall stage may happen for NSs older than 1Myr and even for B fields of the order of 1e12.