Evolution of isolated neutron stars: young coolers and old accretors

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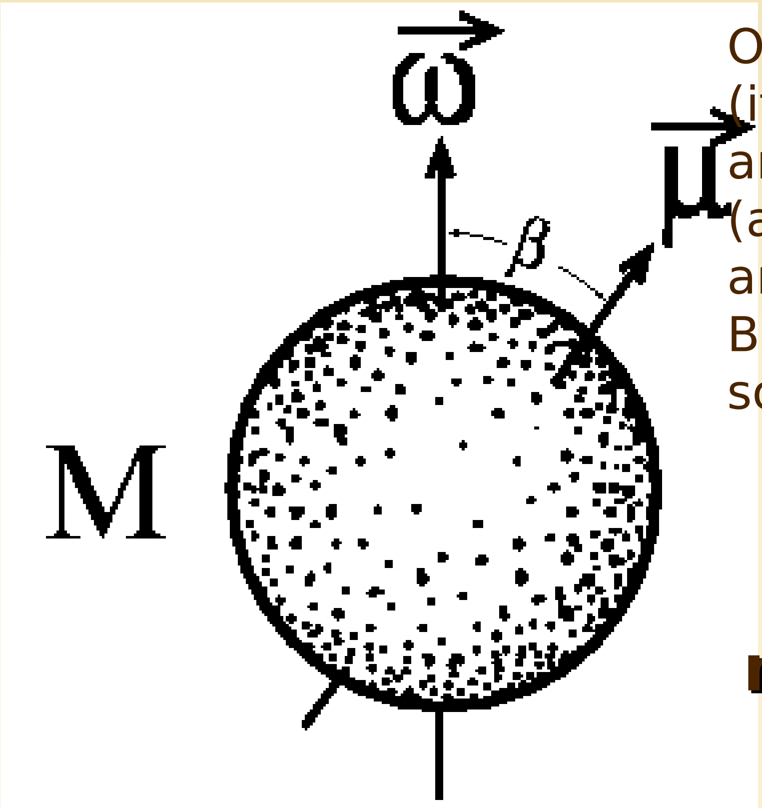
Plan of the talk

- **Introduction:**
  - ✓ Magneto-rotational evolution
  - ✓ Thermal evolution
  - ✓ Types of isolated neutron stars
- **Magnificent seven & Co.**
  - ✓ CCOs and M7
  - ✓ RRATs and M7
  - ✓ Why M7 are not high-B PSRs?
  - ✓ Magnetars, field decay and M7
- **Accreting isolated NSs**
- **Conclusions**

Magnetic rotator



Observational appearances of NSs
(if we are not speaking about cooling)
are mainly determined by P, Pdot, V, B,
(also, probably by the inclination angle β),
and properties of the surrounding medium.
B is not evolving significantly in most cases,
so it is important to discuss spin evolution.

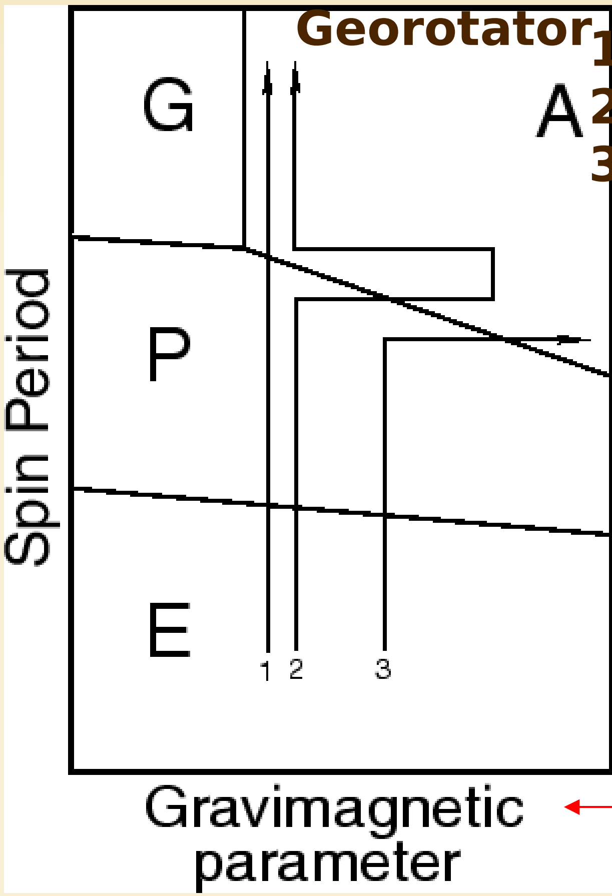
Together with changes in B (and β)
one can speak about
magneto-rotational evolution

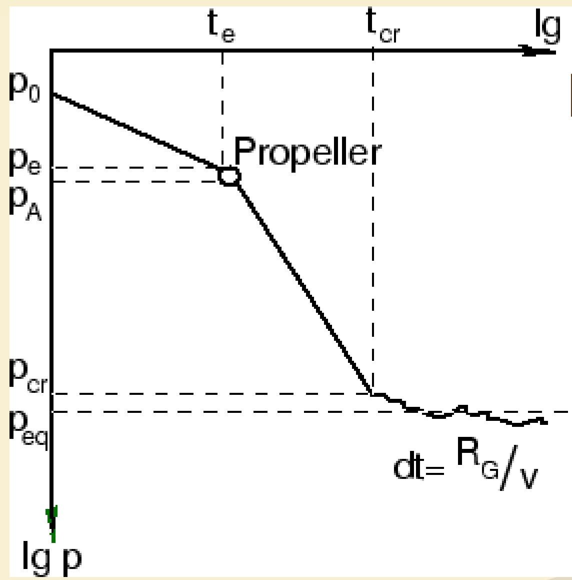
are going to discuss the main stages
his evolution, namely:
tor, Propeller, Accretor, and *Georotator*
owing the classification by Lipunov

Evolution of neutron stars: rotation + magnetic field

Ejector → Propeller → Accretor → Georotator

1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay





[astro-ph/0101031]

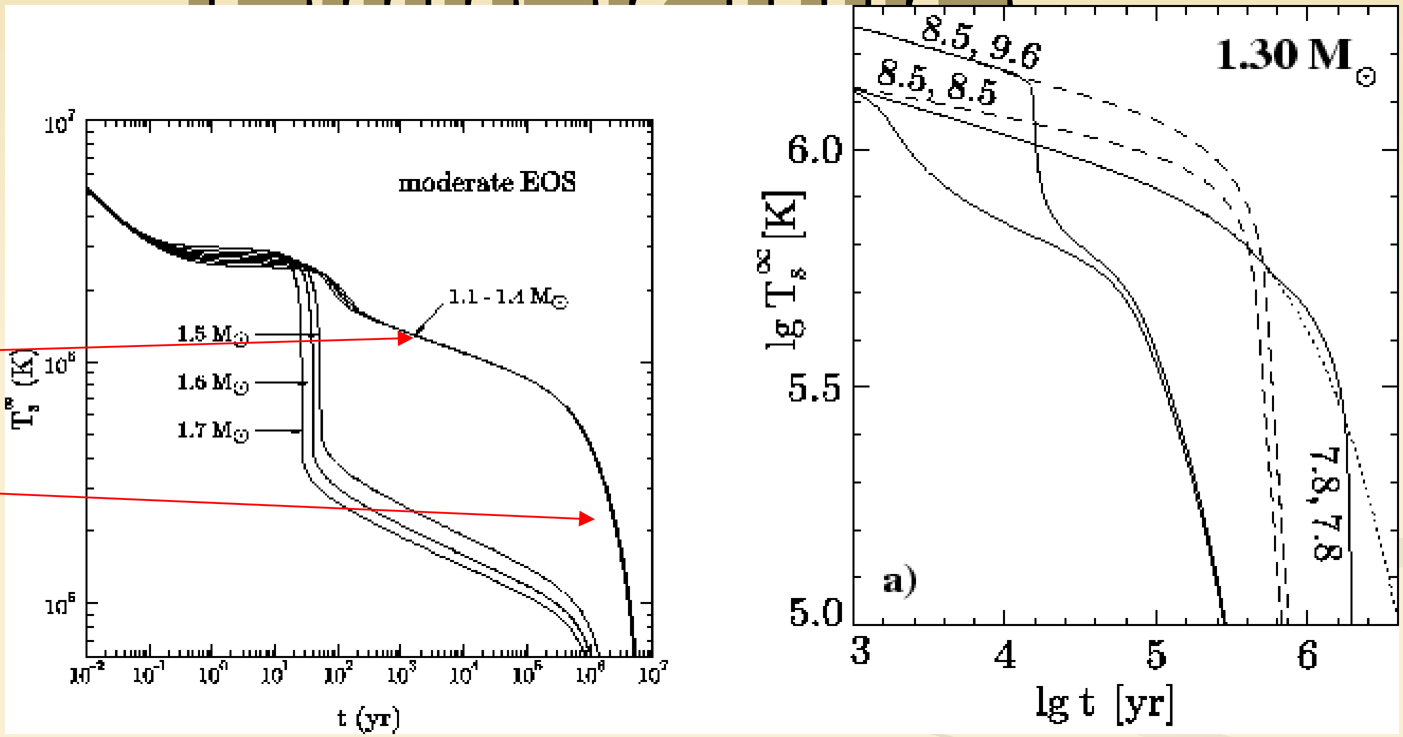
Mdot/μ^2

See the book by Lipunov (1987, 1992)

Evolution of NSs: temperature

eutrino
ooling stage

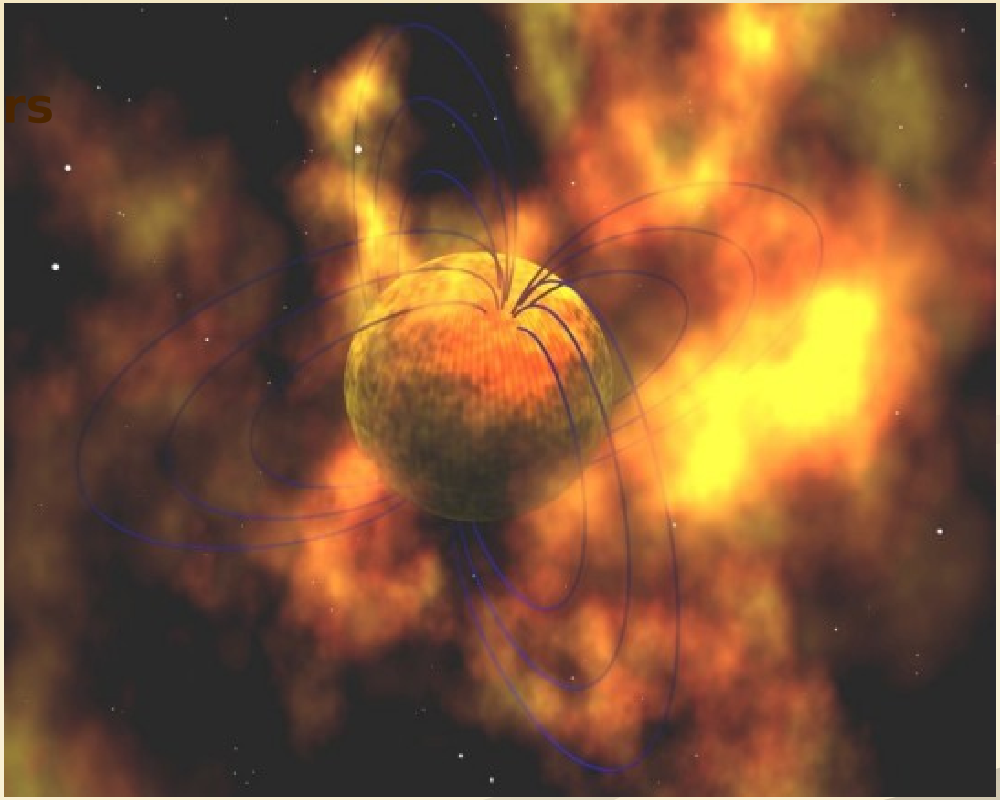
Photon
ooling stage



[Yakovlev et al. (1999) Physics Uspekhi]

The new zoo of neutron stars

During last >10 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.



- Compact central X-ray sources in supernova remnants.
- Anomalous X-ray pulsars
- Soft gamma repeaters
- The Magnificent Seven
- Unidentified EGRET sources
- Transient radio sources (RRATs)
- Calvera ….

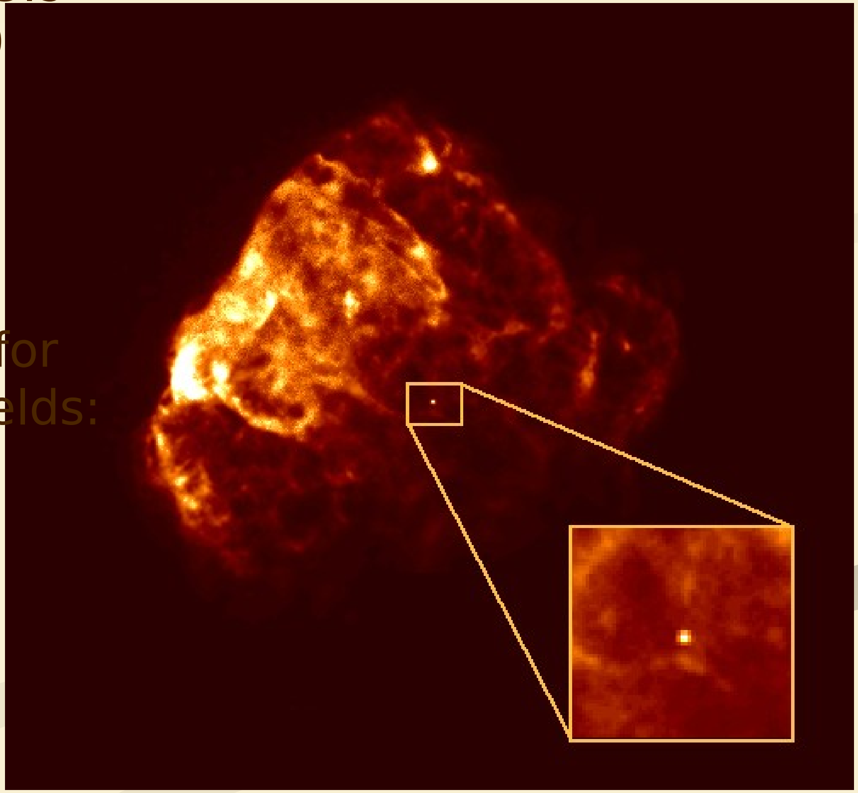
[see some brief review in astro-ph/0610593]

CCOs in SNRs

		Age	Distance
2327.9+584843	Cas A	0.32	3.3–3.7
5201.4−461753	G266.1−1.2	1–3	1–2
2157.5−430017	Pup A	1–3	1.6–3.3
1000.8−522628	G296.5+10.0	3–20	1.3–3.9
5238.6+004020	Kes 79	~9	~10
1328.4−394955	G347.3−0.5	~10	~6

Pavlov, Sanwal, Teter: astro-ph/0311526,
de Luca: arxiv:0712.2209]

r two sources there are strong indications for
all initial spin periods and low magnetic fields:
1207.4-5209 in PKS 1209-51/52 and
R J1852+0040 in Kesteven 79
e Halpern et al. arxiv:0705.0978]



Known magnetars

SGRs

- 0526-66
- 1627-41
- 1806-20
- 1900+14
- +candidates

AXPs

- CXO 010043.1-72
- 4U 0142+61
- 1E 1048.1-5937
- CXOU J164710.3-
- 1 RXS J170849-40
- XTE J1810-197
- 1E 1841-045
- AX J1844-0258
- 1E 2259+586
- +candidates and transients

(CTB 109)

The most recent SGR candidate was discovered in Aug. 2008 (GCN 8112 Holla
It is named SGR 0501+4516. Several reccurent (weak?) bursts have been dete
several experiments (see, for example, GCN 8132 by Golenetskii et al.).
Spin period 5.769 sec. Optical and IR counterparts.

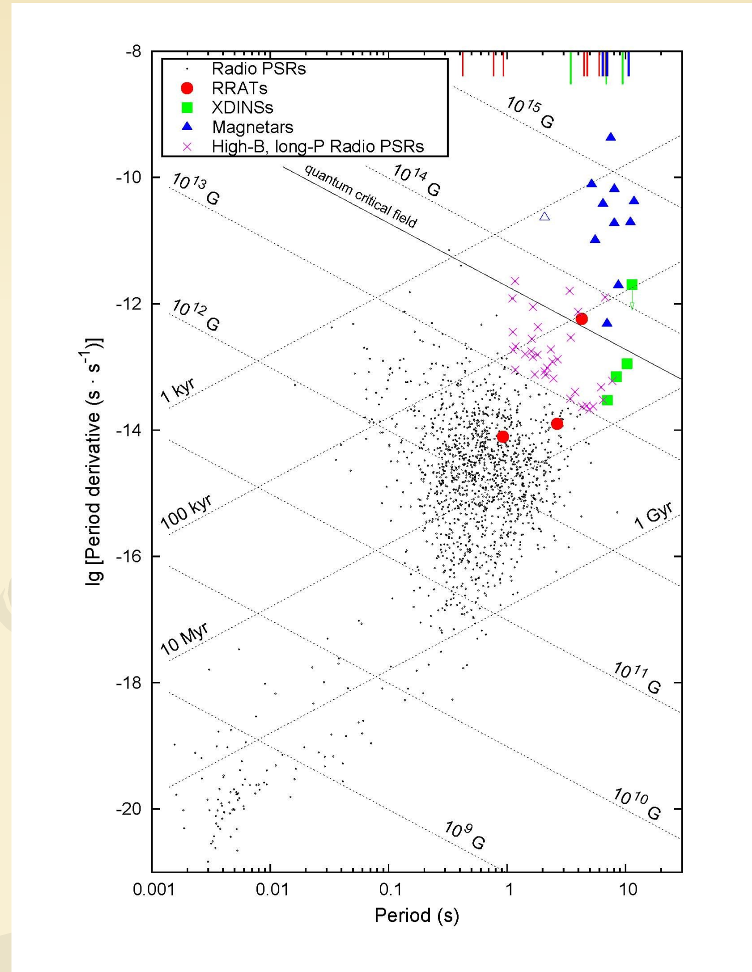
Magnificent Seven

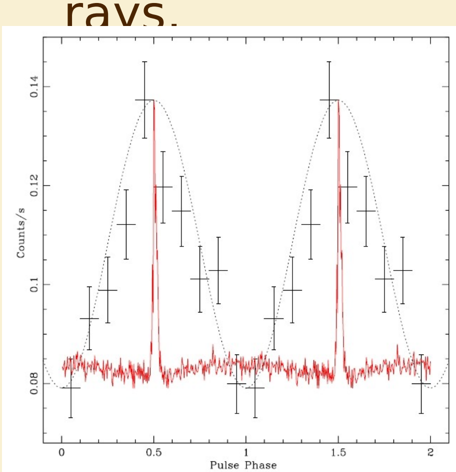
Name	Period, s
RX 1856	7.05
RX 0720	8.39
RBS 1223	10.31
RBS 1556	6.88?
RX 0806	11.37
RX 0420	3.45
RBS 1774	9.44

Radioquiet (?)
Close-by
Thermal emission
Absorption features
Long periods

RRATs

- 11 sources detected in the
  Parkes Multibeam survey
  (McLaughlin et al 2006)
- Burst duration 2-30 ms, interval 4 min-3 hr
- Periods in the range 0.4-7 s
- Period derivative measured in 3 sources:
  B ~ 10^{12}-10^{14} G, age ~ 0.1-3 Myr
- RRAT J1819-1458 detected in the X-rays.
  ...nd thermal,
  ...eynolds et al 2006)





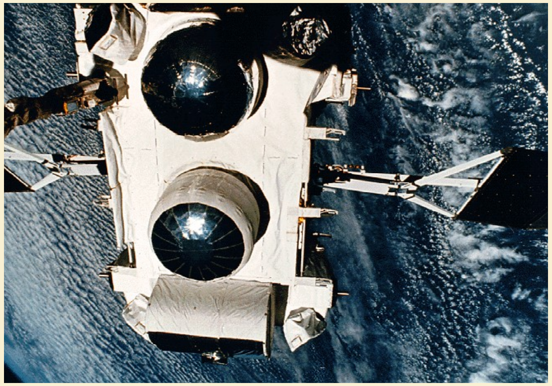
Unidentified EGRET sources

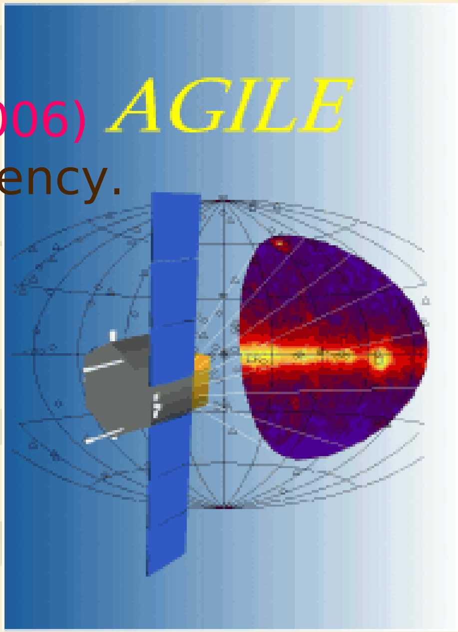
er (2000), Gehrels et al. (2000)
ntified sources are divided into several groups.
f them has sky distribution similar to the Gould Belt objects.

uggested that GLAST (and, probably, AGILE) can help to solve this problem.

ely studied subject
or example papers by Harding, Gonthier)

adio pulsars in 56 EGRET error boxes (Crawford et al. 2006)
ever, Keith et al. (0807.2088) found a PSR at high frequency.



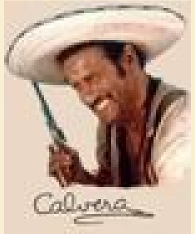


Calvera et al.

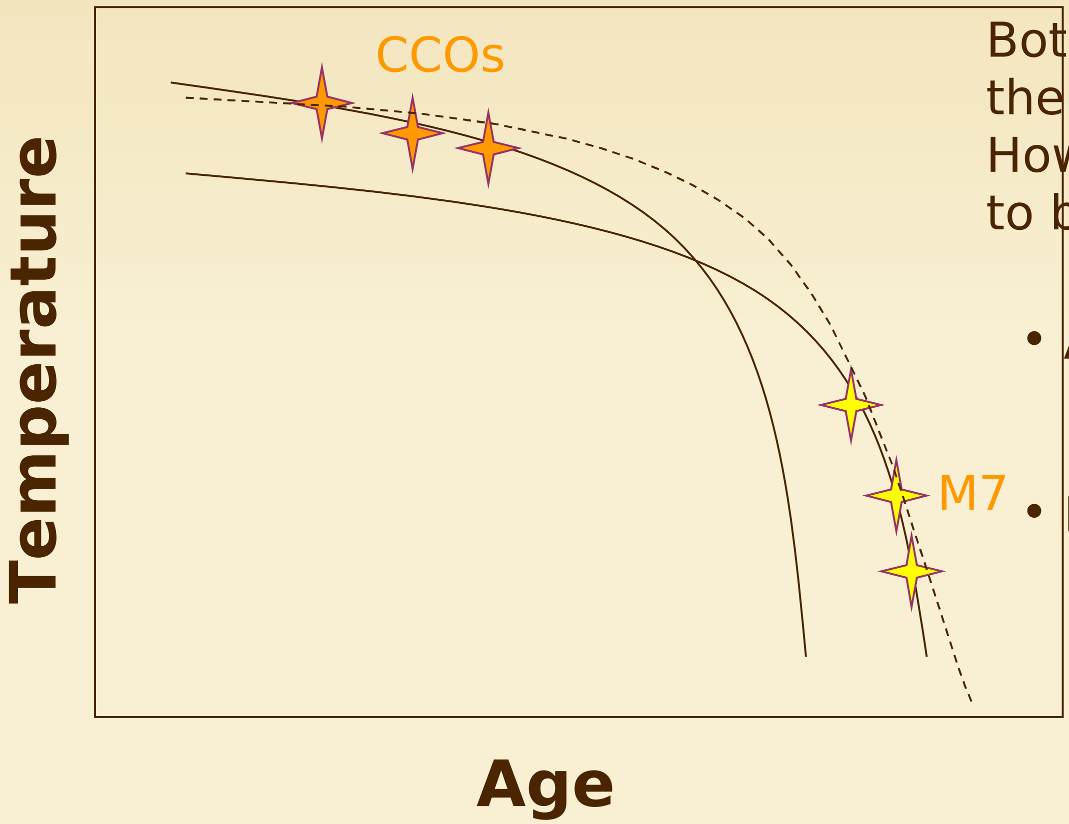
ently, Rutledge et al. reported the discovery of an enigmatic
andidated dubbed *Calvera*.

n be an evolved (aged) version of Cas A source,
also it can be a M7-like object, who’s progenitor was
naway (or, less probably, hypervelocity) star.

adio emission was found (arxiv:0710.1788).



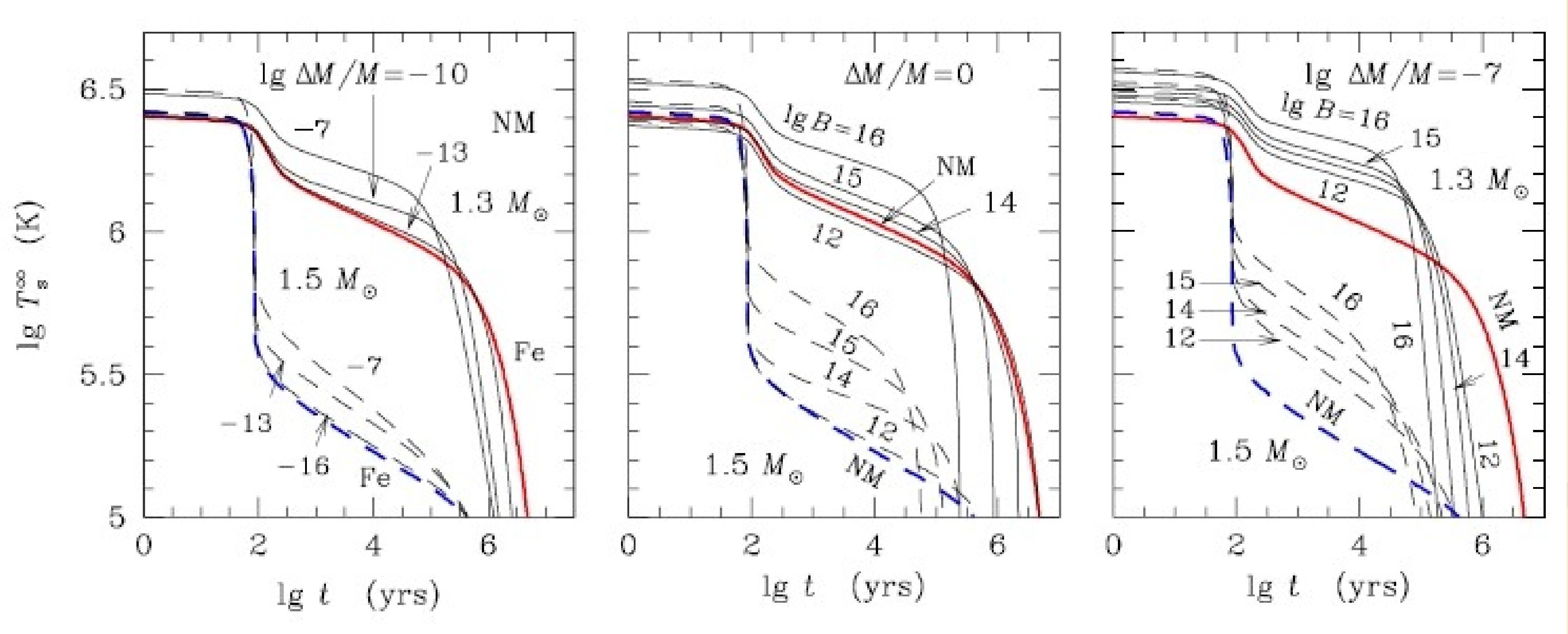
M 7 and CCOs



Both CCOs and M7 seem to be
the hottest at their ages (10^3 and 10^6
However, the former cannot evolve
to become the latter ones!

- Accreted envelopes (presented in CCOs, absent in the M7)
- Heating by decaying magnetic fiel in the case of the M7

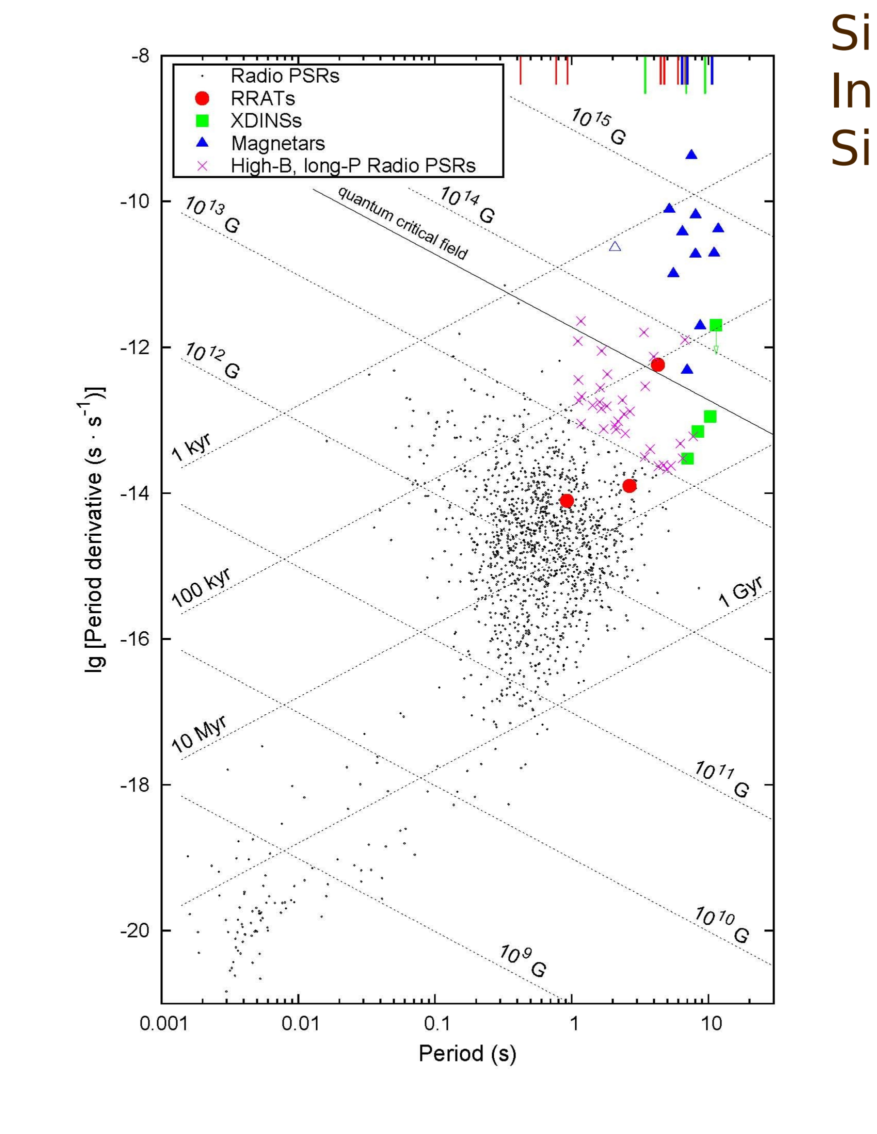
Accreted envelopes, B or heating?



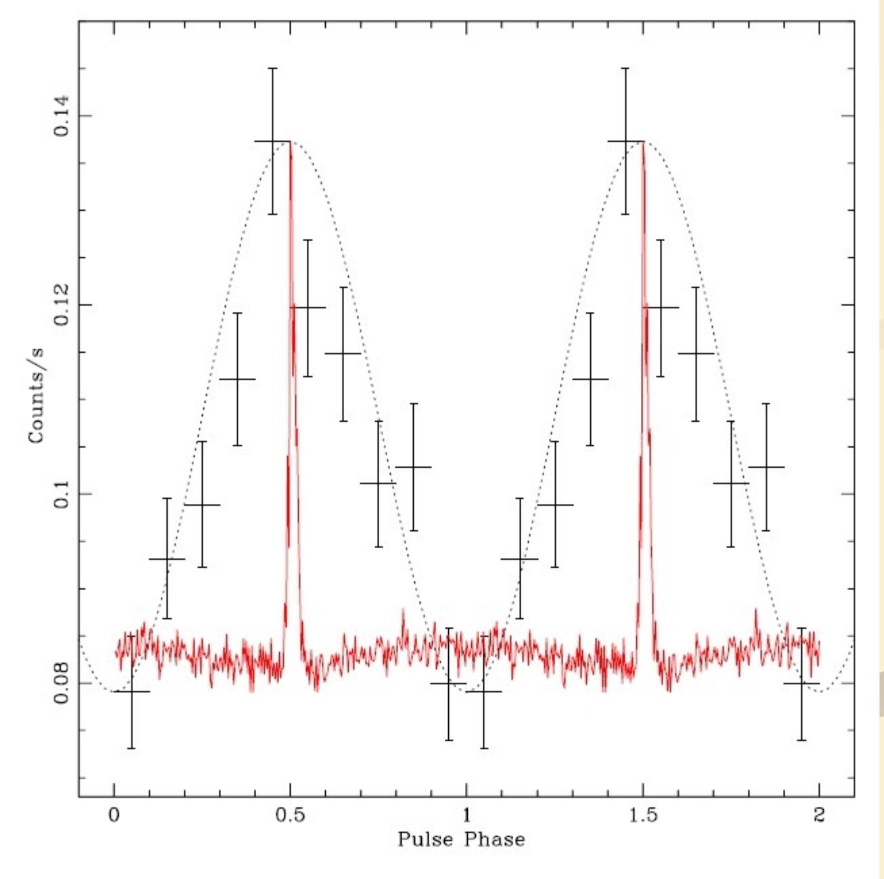
(Yakovlev & Pethick 2004)

ecessary to make population synthesis studies to test all these possibilities.

M7 and RRATs



Similar periods and Pdots
In one case similar thermal properties
Similar birth rate?



(arXiv: 0710.2056)

M7 and RRATs: pro et contra

ed on similarities between M7 and RRATs it was proposed that they can be
erent manifestations of the same type of INSs (astro-ph/0603258).
verify it a very deep search for radio emission (including RRAT-like bursts)
s peformed on GBT (Kondratiev et al.).
ddition, objects have been observed with GMRT (B.C.Joshi, M. Burgay et al.).

oth studies only upper limits were derived.
, the zero result can be just due to unfavorable orientations
long periods NSs have very narrow beams).
 necessary to increase statistics.

XDINS	Pulsed emission			Bursty emission		
	$S_{\rm lim}$ (μJy)	$L_{1400}^{\rm p,max}$ (mJy kpc^2)	$L_{820}^{\rm p,max}$ (mJy kpc^2)	rate upper limit (hr^{-1})	$S_{\rm lim}^{\rm burst}$ (mJy)	$L_{1400}^{\rm b,max}$ (mJy kpc^2)
RX J0720.4−3125	8	$4 \cdot 10^{-4}$	10^{-3}	0.25	21	1
RX J0806.4−4123	10	$4 \cdot 10^{-3}$	10^{-2}	0.32	18	6.9
RX J1308.6+2127	10	$4 \cdot 10^{-3}$	10^{-2}	0.24	17	6.5
RX J1605.3+3249	8	$3 \cdot 10^{-3}$	$8 \cdot 10^{-3}$	0.25	22	8.4
RX J1856.5−3754	14	$1.4 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$	0.32	24	0.2
RX J2143.0+0654	13	$5 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$	0.36	20	7.6

Kondratiev et al, in press, see also arXiv: 0710.1648)

M7 and high-B PSRs

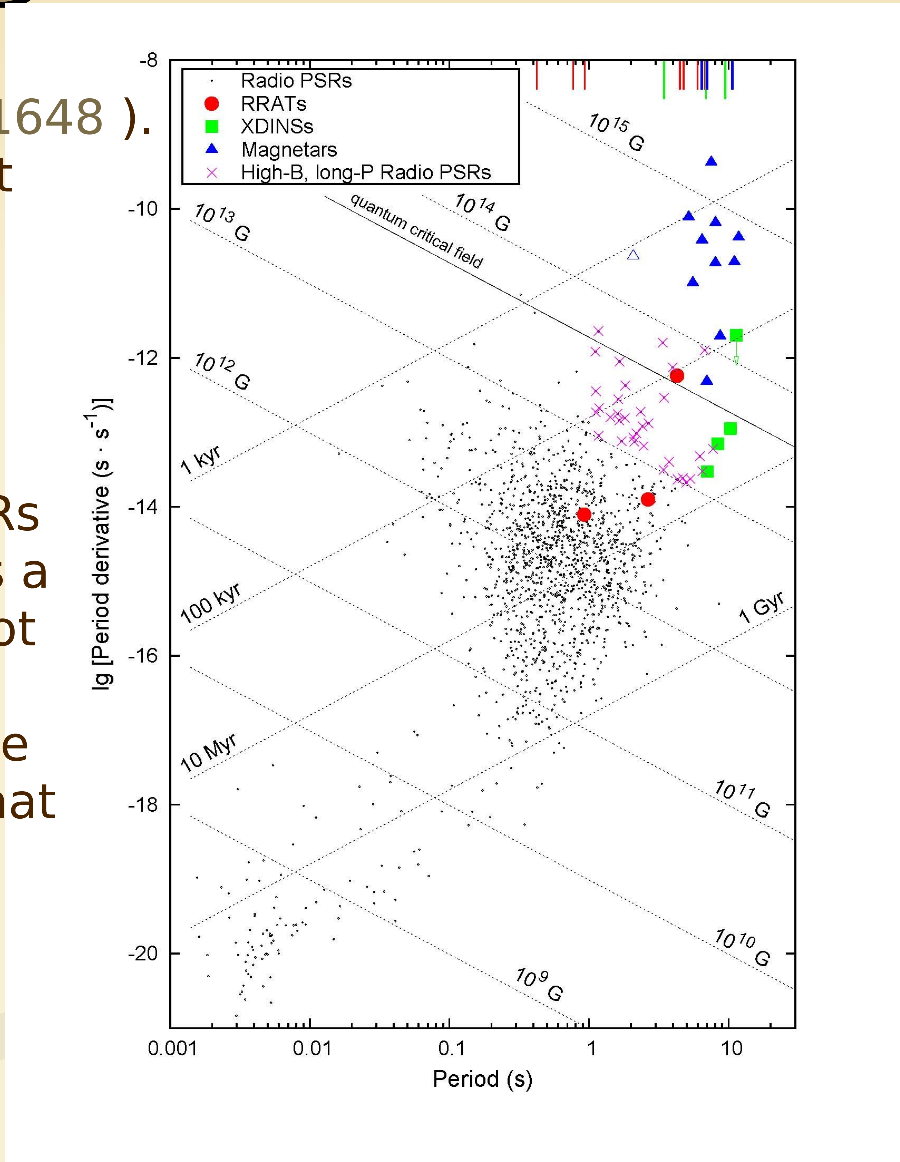
g limits on radio emission from the M7 stablished (Kondratiev et al. 2008: 0710.1648). ver, observationally it is still possible that 7 are just misaligned high-B PSRs.

e there any other considerations to verify a link between these two popualtions of NSs?

ost of population synthesis studies of PSRs magnetic field distribution is described as a ssian, so that high-B PSRs appear to be not numerous.

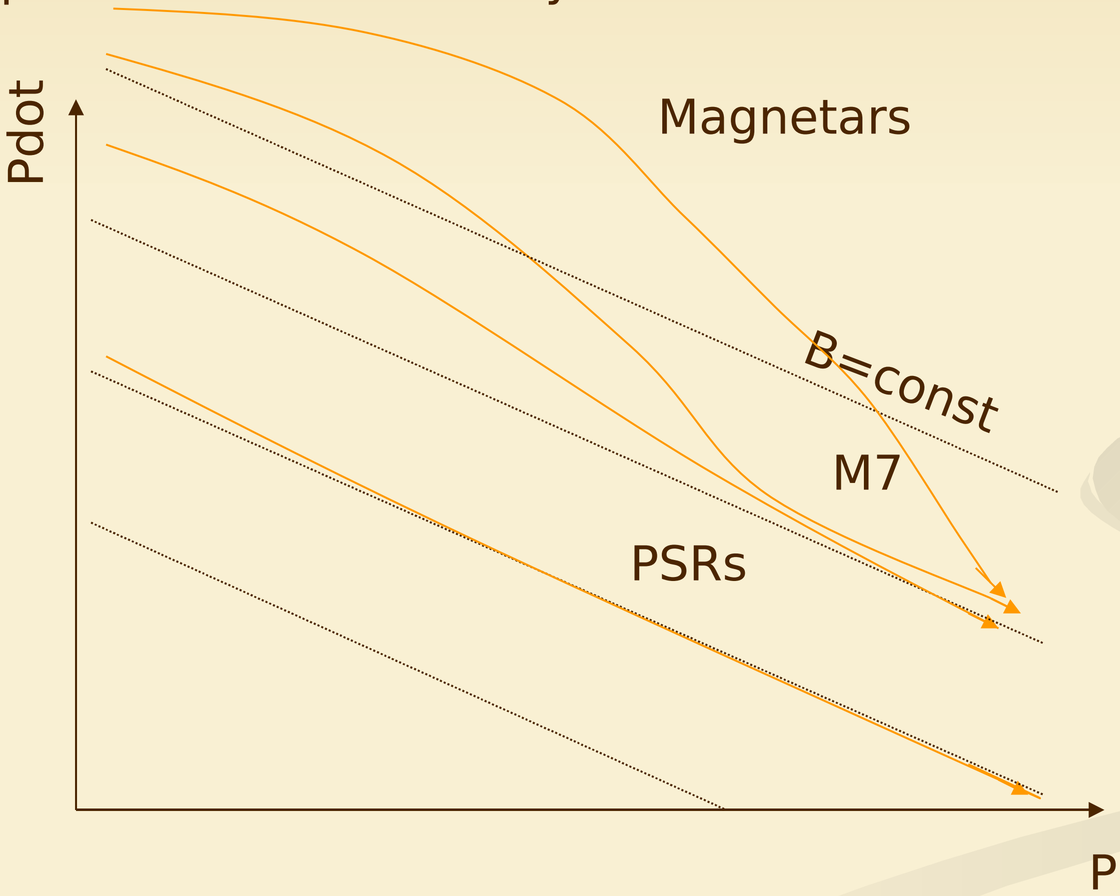
he other hand, population synthesis of the population of young NSs demonstrate that M7 are as numerous as normal-B PSRs.

So, for standard assumptions t is much more probable, that high-B PSRs and the M7 are not related.



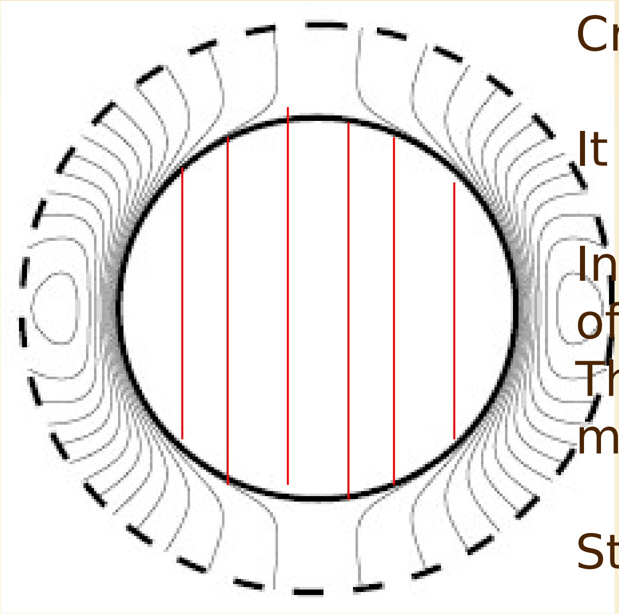
Magnetars, field decay, heating

nodel based on field-dependent decay of the magnetic moment of NSs
provide an evolutionary link between different populations.



Magnetic field decay

Magnetic fields of NSs are expected to decay due to decay of currents which support them.



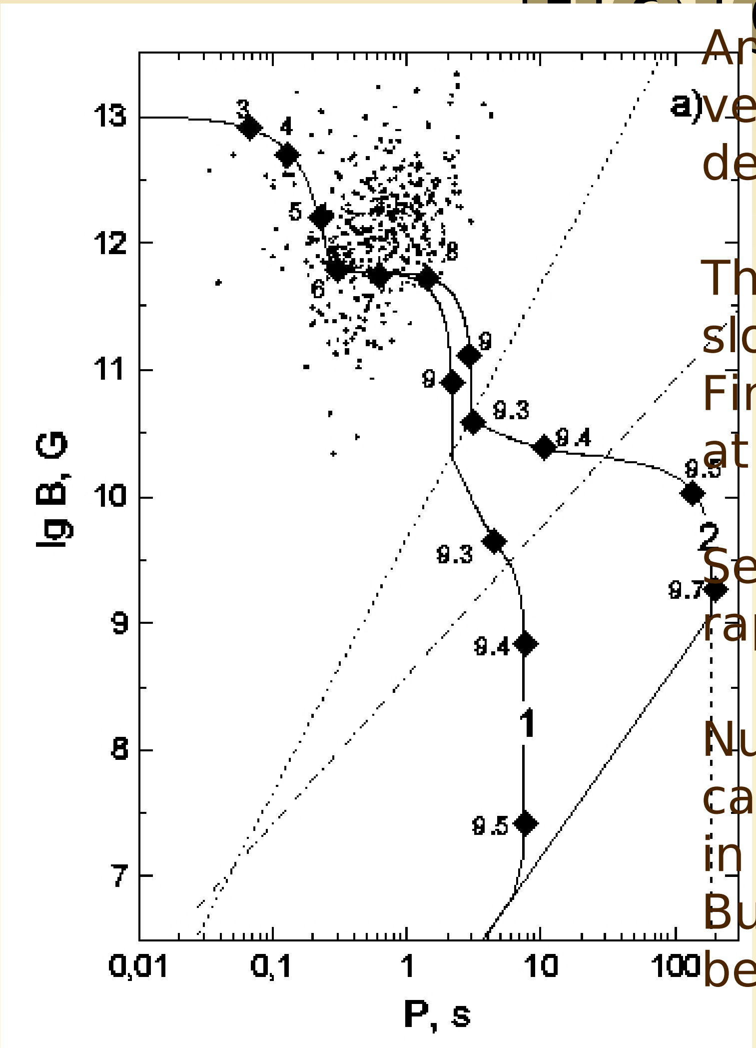
Crustal field of core field?

It is easy to decay in the crust.

In the core the filed is in the form
of superconducting vortices.
They can decay only when they are
moved into the crust (during spin-down).

Still, in most of models strong fields decay.

Period evolution with field decay



An evolutionary track of a NS is very different in the case of decaying magnetic field.

The most important feature is slow-down of spin-down. Finally, a NS can nearly freeze at some value of spin period.

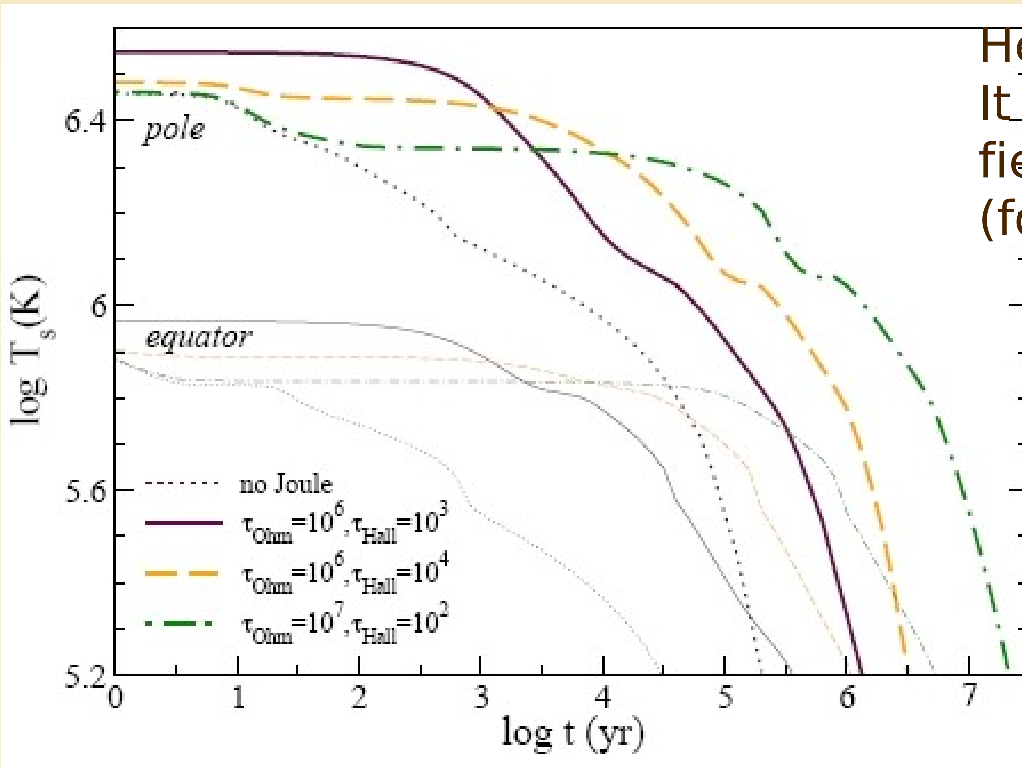
Several episodes of relatively rapid field decay can happen.

Number of isolated accretors can be both decreased or increased in different models of field decay. But in any case their average periods become shorter and temperatures lower.

astro-ph/9707318

Magnetic field decay vs. thermal evolution

gnetic field decay can be an important source of NS heating.



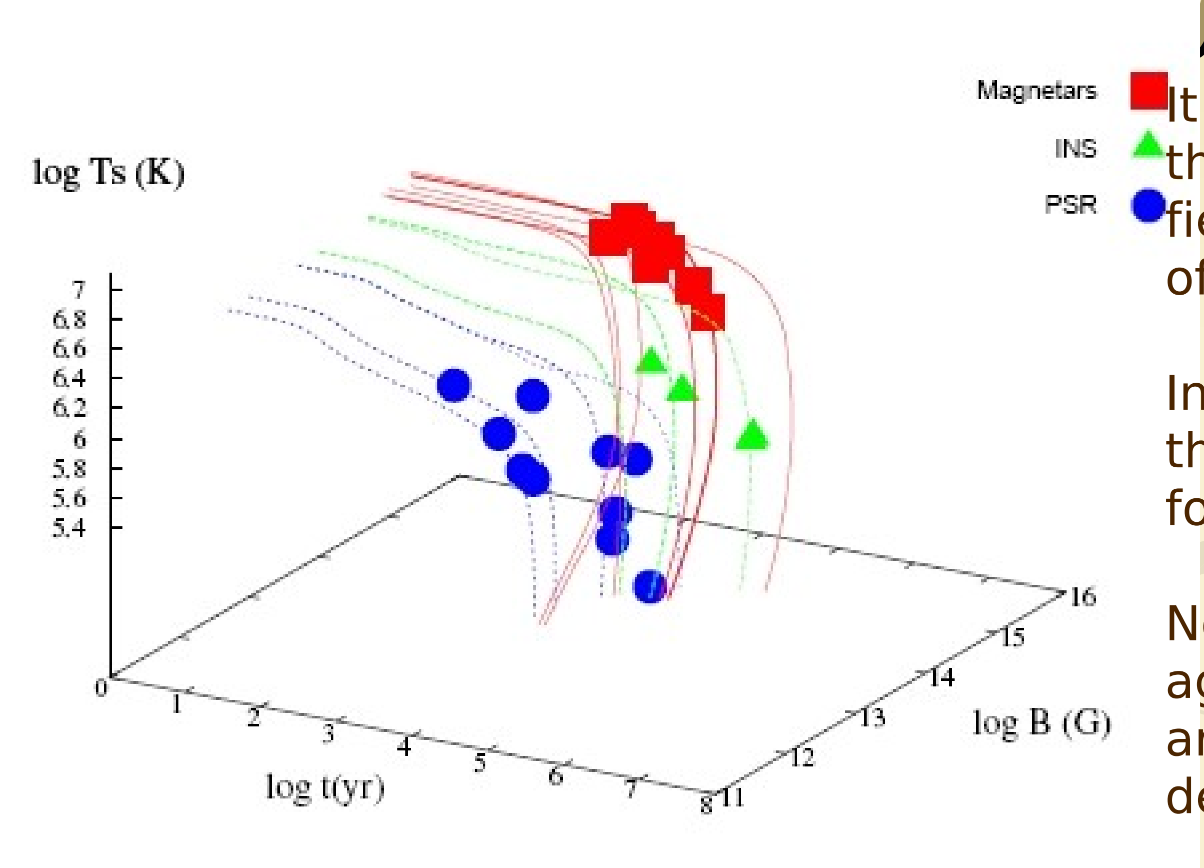
Heat is carried by electrons.
It is easier to transport heat along field lines. So, poles are hotter.
(for light elements envelope the situation can be different).

Ohm and Hall decay

$$B = B_0 \frac{\exp\left(-t/\tau_{\mathrm{Ohm}}\right)}{1 + \frac{\tau_{\mathrm{Ohm}}}{\tau_{\mathrm{Hall}}}\left(1 - \exp\left(-t/\tau_{\mathrm{Ohm}}\right)\right)}$$

arxiv:0710.0854 (Aguilera et al.)

Joule heating for everybody?



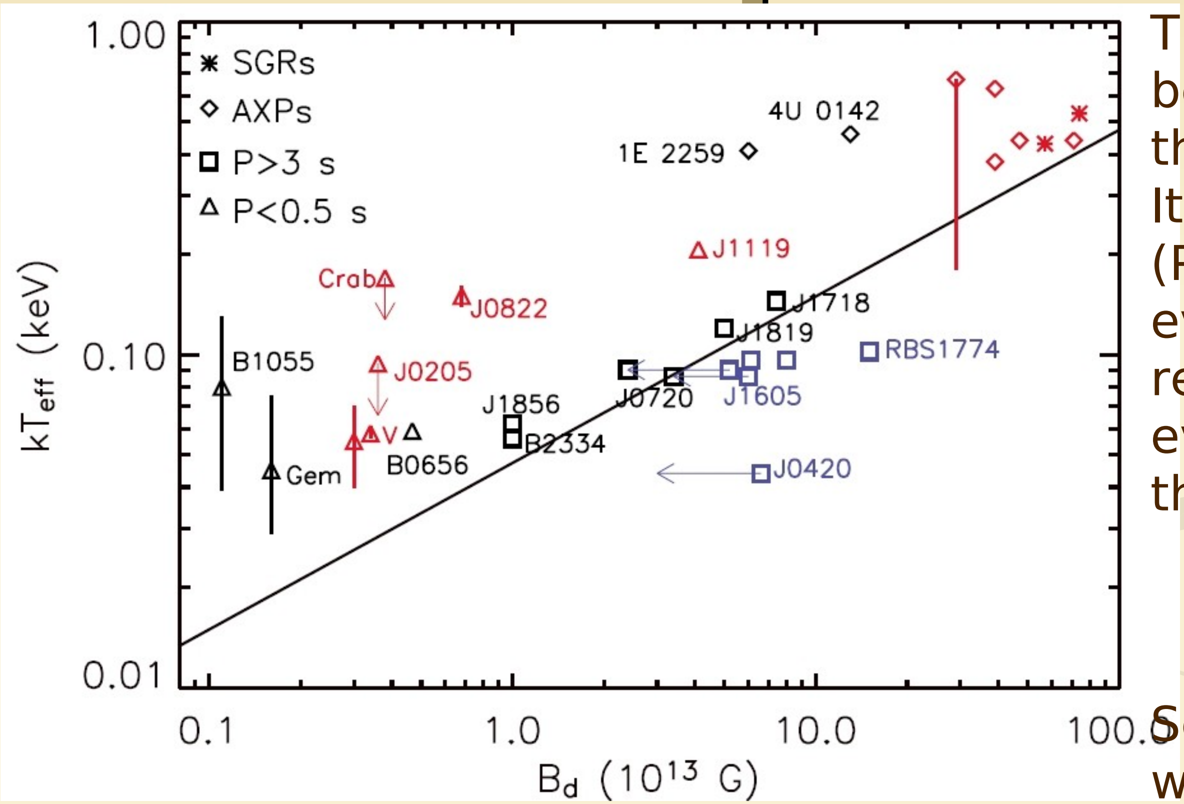
It is important to understand the role of heating by the field decay for different types of INS.

In the model by Pons et al. the effect is more important for NSs with larger initial B.

Note, that the characteristic age estimates (P/2 Pdot) are different in the case of decaying field!

arXiv: 0710.4914 (Aguilera et al.)

Magnetic field vs. temperature



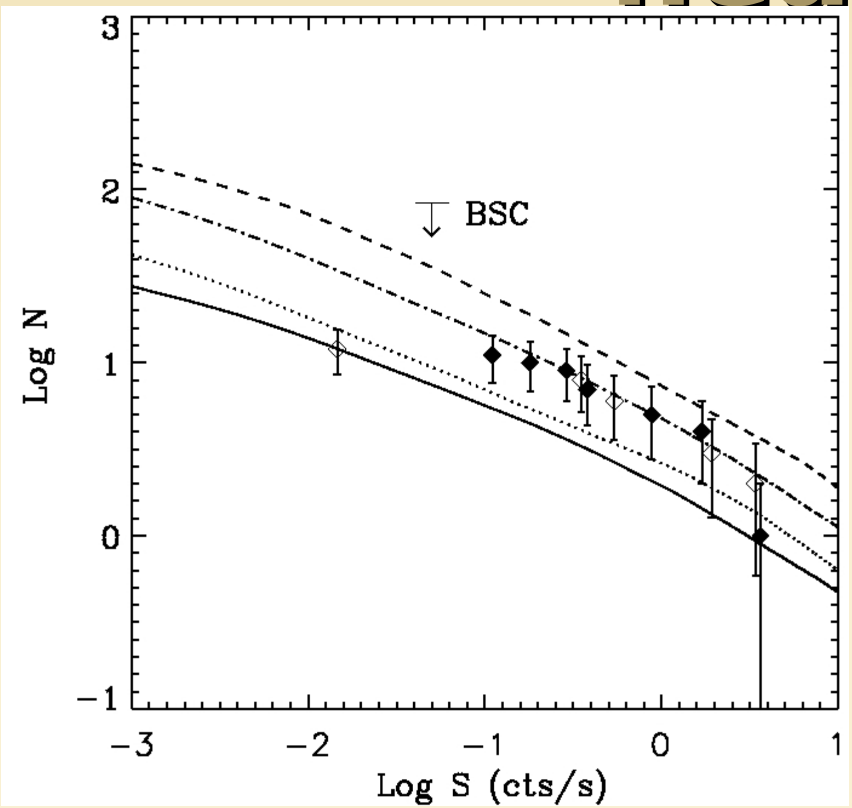
(astro-ph/0607583)

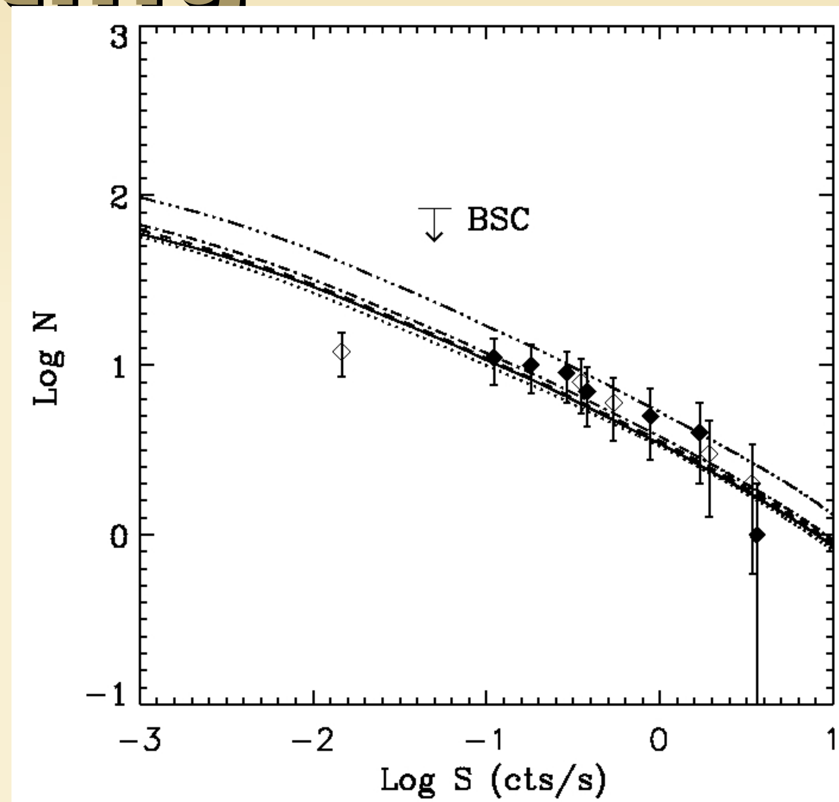
The line marks balance between heating due to the field decay and cooling. It is expected by the authors (Pons et al.) that a NS evolves downwards till it reaches the line, then the evolution proceeds along the line.

$$\mathbf{T_{eff} \sim B_d^{1/2}}$$

Selection effects are not well studied here. A kind of population synthesis modeling is welcomed.

Log N – Log S with heating





Log N – Log S for 4 different magnetic fields.

Different magnetic field distributions.

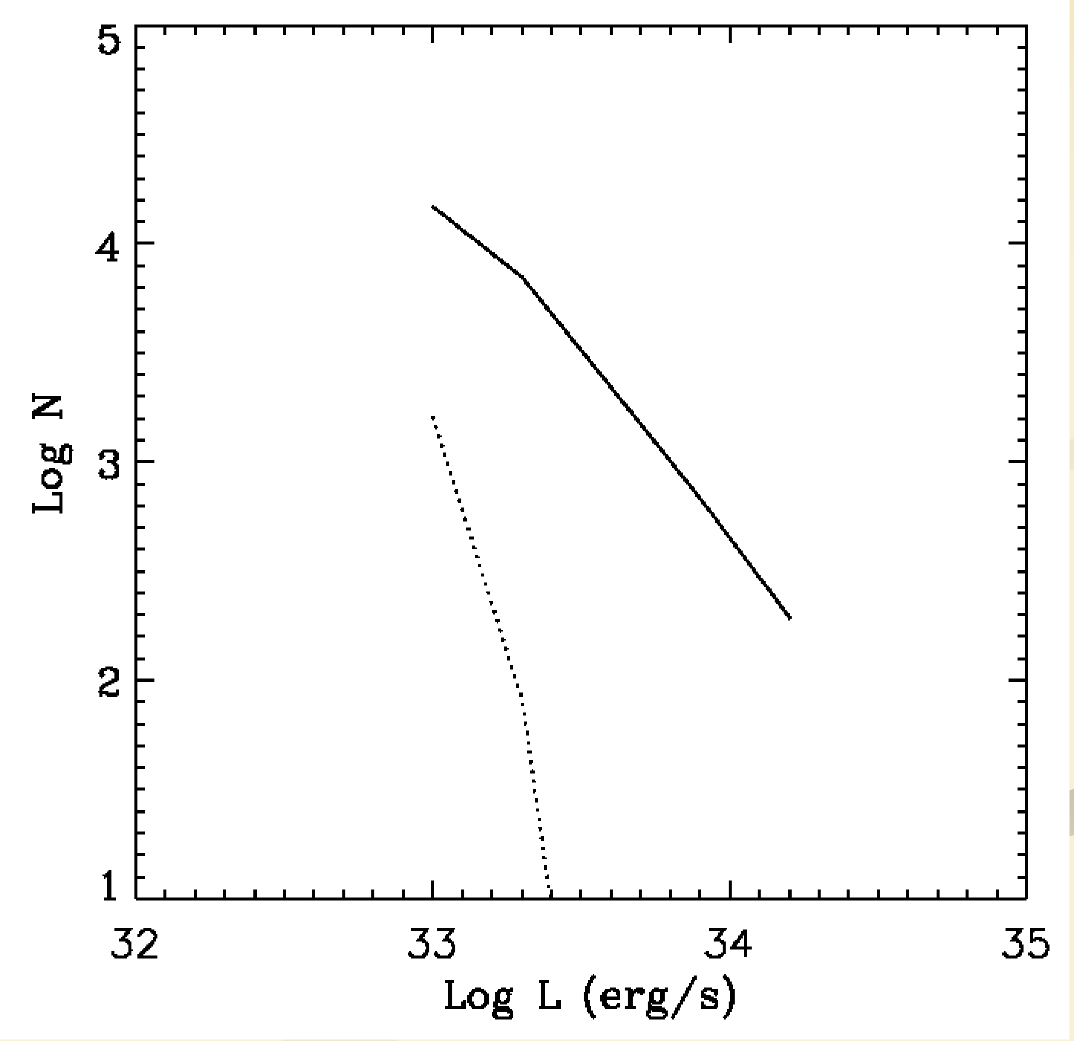
1. No heating ($<10^{13}$ G)
2. $5\ 10^{13}$ G
3. 10^{14} G
4. $2\ 10^{14}$ G

ov, Pons, work in progress; the code used in Posselt et al. A&A (2008) with modif

Log N – Log L

Two magnetic field distributions: with and without magnetars (i.e. different magnetic field distributions are used).
5 values of inital magnetic field, 8 masses of NSs.
SNR 1/30 yrs^{-1}.

"Without magnetars" means "no NSs with $B_0 > 10^{13}$ G".

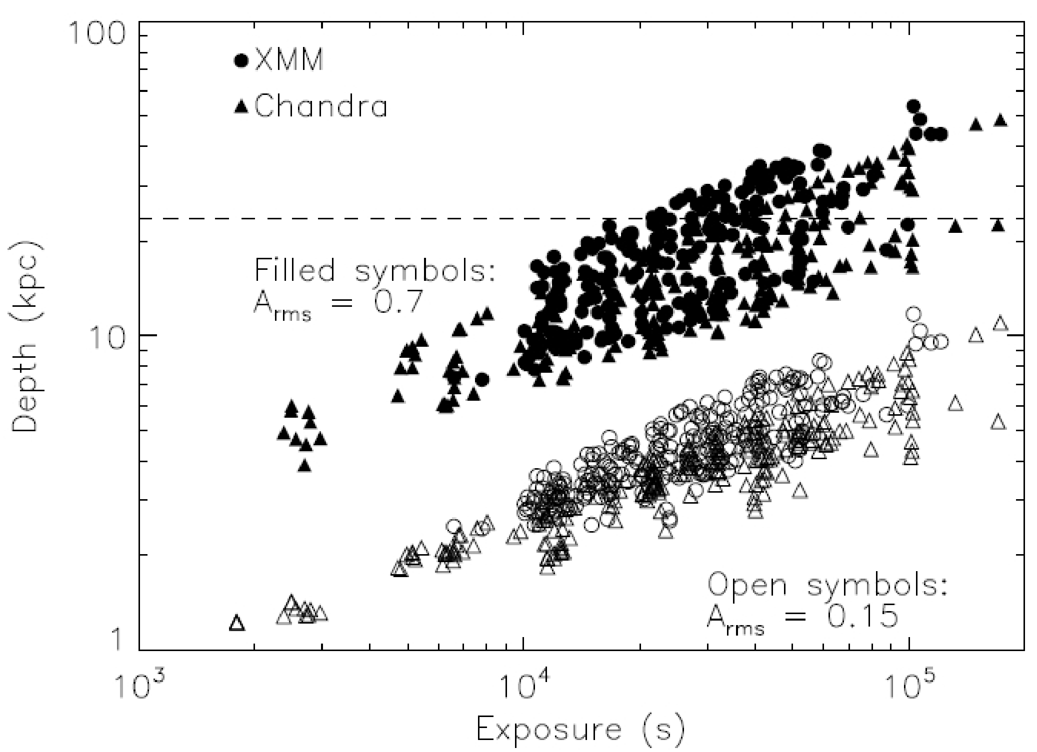


[Popov, Pons, work in progress]

Populations ....

irthrate of magnetars is uncertain
ue to discovery of transient sources
ust from “standard” SGR statistics
is just 10%, then, for example,
he M7 cannot be aged magnetars
ith decayed fields, but if there are
nany transient AXPs and SGRs –
hen the situation is different.

mits, like the one by Muno et al.,
n the number of AXPs from a
earch for periodicity are very
nportant and have to be improved
a task for eROSITA?).

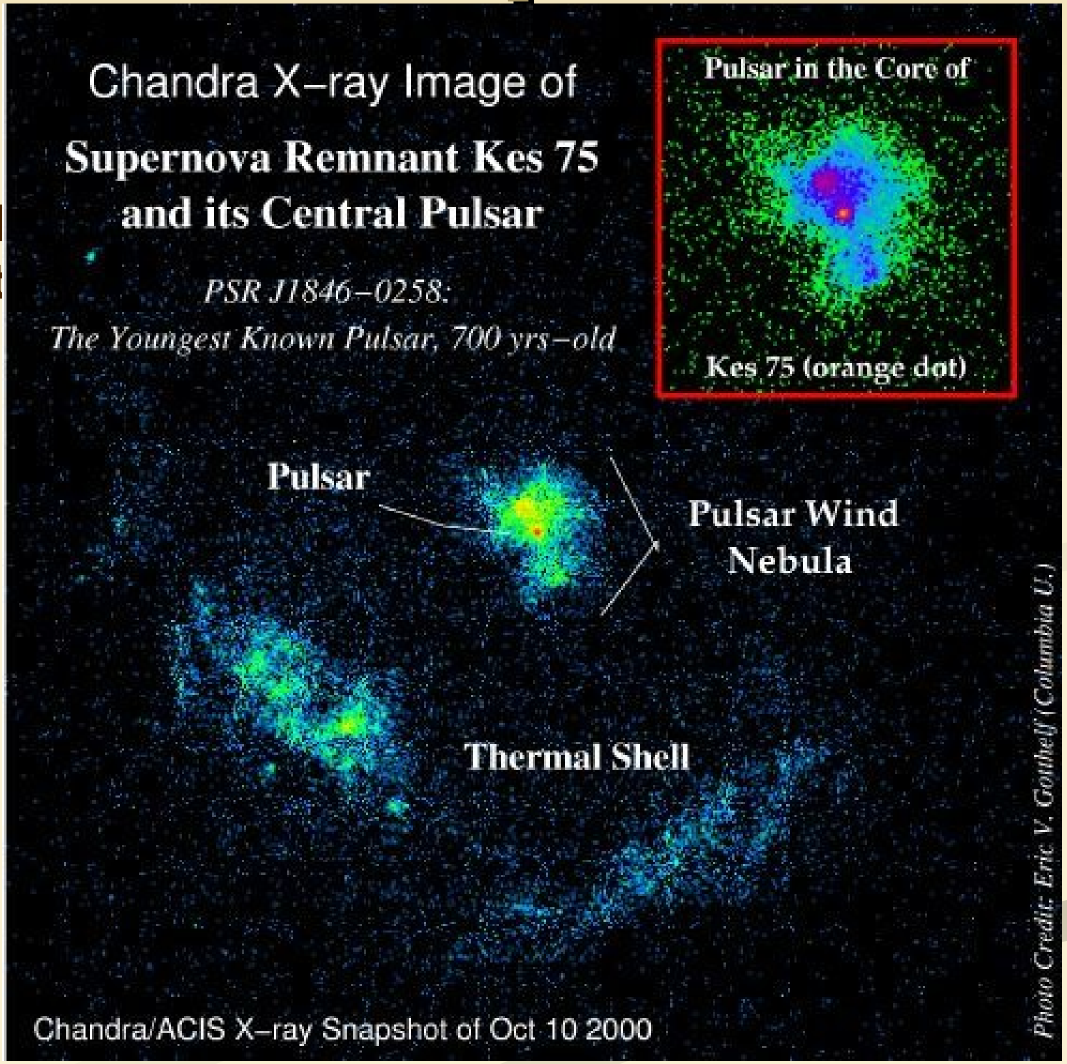


$L_x > 3\ 10^{33}$ erg s^{-1}

[Muno et al. 2007]

Transient radiopulsar

PSR J1846-0258
P=0.3 sec
B=5 10^{13} G
Among all rotation powered PSRs it has the largest Edot



The pulsar increased
its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts.
Timing noise.

dditional info about this pulsar at the web-site
/hera.ph1.uni-koeln.de/~heintzma/SNR/SNR1_IV.htm

0802.1242, 0802.1704

Accreting isolated neutron stars

Why are they so important?

- Can show us how old NSs look like
  ١. Magnetic field decay
  ٢. Spin evolution
- Physics of accretion at low rates
- NS velocity distribution
- New probe of NS surface and interiors
- ISM probe

Critical periods for isolated NSs

$$P_E(E \to P) \simeq 10\,\mu_{30}^{1/2}\,n^{-1/4}\,v_{10}^{1/2}\ \mathrm{s}$$

ransition from Ejector to Propeller (supersonic)

$$t_E \simeq 10^9\,\mu_{30}^{-1}\,n^{-1/2}\,v_{10}\ \mathrm{yr}$$

Duration of the ejector stage

$$P_A(P \to A) \simeq 420\,\mu_{30}^{6/7}\,n^{-3/7}\,v_{10}^{9/7}\ \mathrm{s}$$

Transition from supersonic Propeller to subsonic Propeller or Accretor

$$P_{eq} = 2.6 \times 10^3\,v_{(t)10}^{-2/3}\,\mu_{30}^{2/3}\,n^{-2/3}\,v_{10}^{13/3}\ \mathrm{s}$$

A kind of equilibrium period for the case of accretion from turbulent medium

$$v < 410\,n^{1/10}\,\mu_{30}^{-1/5}\ \mathrm{km\,s^{-1}}$$

Condition for the Georotator formation (instead of Propeller or Accretor)

(see, for example, astro-ph/9910114)

Expected properties

ccretion rate

upper limit can be given by the Bondi formula:

ot = $\pi R_G^2 \rho v$, $R_G \sim v^{-2}$

ot = 10^{11} g/s (v/10 km/s)$^{-3}$ n

0.1 Mdot $c^2 \sim 10^{31}$ erg/s

wever, accretion can be smaller due to the influence of a magnetosphere of a NS
ee numerical studies by Toropina et al.).

eriods

ods of old accreting NSs are uncertain, because we do not know evolution
enough.

$$p_{\rm A} = 2^{5/14}\pi(GM)^{-5/7}(\mu^2/\dot{M})^{3/7} \simeq$$

$R_A = R_{co}$

$$300\,\mu_{30}^{6/7}(v/10\,{\rm km\,s^{-1}})^{9/7}n^{-3/7}\,{\rm s.}$$

Subsonic propeller

n after $R_{co}>R_A$ accretion can be inhibited.
have been noted already in the pioneer papers by Davies et al.

to rapid (however, subsonic) rotation a hot envelope is formed around
magnetosphere. So, a new critical period appear.

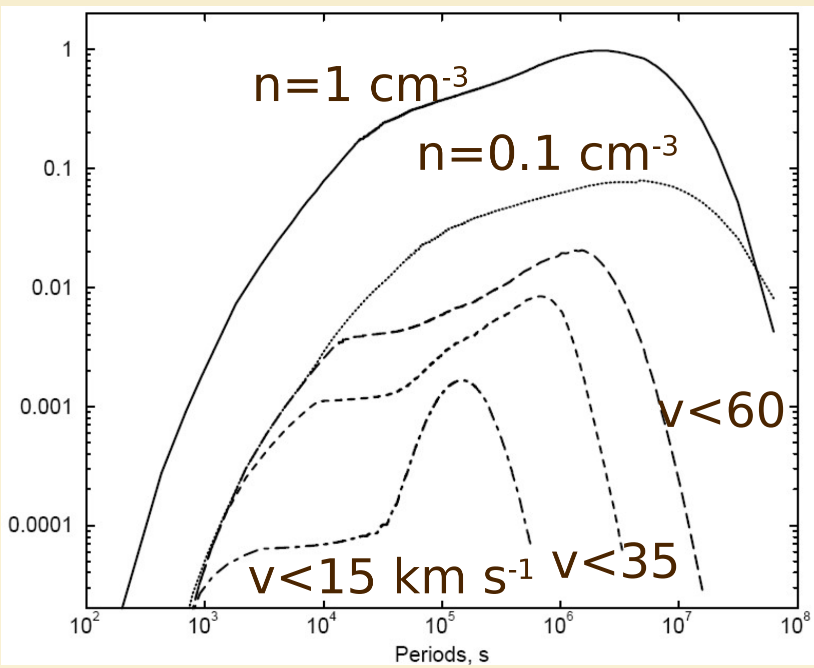
$$P_{\rm br} \simeq \ 450\ \mu_{30}^{16/21}\ \dot{M}_{15}^{-5/7}\ m^{-4/21}\ {\rm s.}$$

(Ikhsanov astro-ph/0310076)

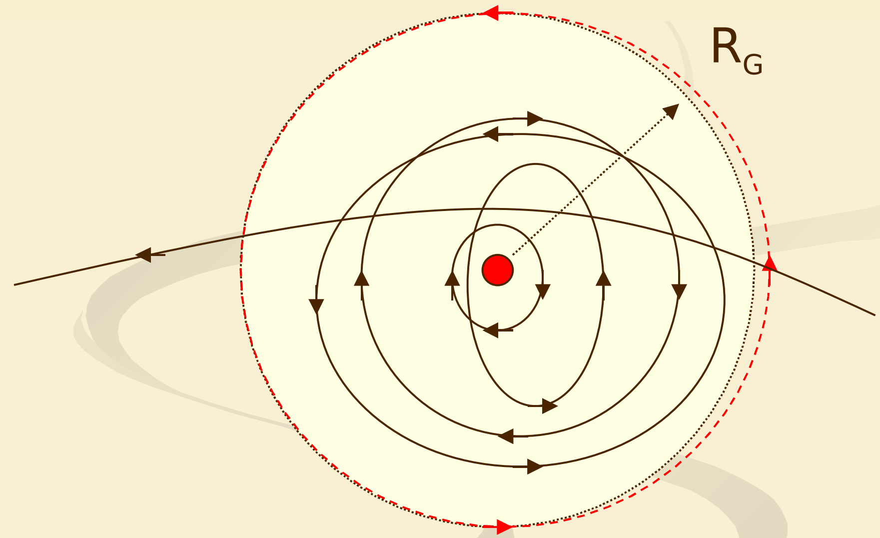
f this stage is realized (inefficient cooling) then
- accretion starts later
- accretors have longer periods

Equilibrium period

stellar medium is turbulized. If we put a non-rotating NS in the ISM,
because of accretions of turbulized matter it'll start to rotate.
clearly illustrates, that a spinning-down accreting isolated NS in a realistic ISM
ld reach some equilibrium period.



[A&A 381, 1000 (2002)]



$$P_{eq} = 2.6 \times 10^3\, v_{(t)10}^{-2/3}\, \mu_{30}^{2/3}\, n^{-2/3}\, v_{10}^{13/3}\ \mathrm{s}$$

A kind of equilibrium period for the case of accretion from turbulent medium

Expected properties-2

mperatures

pend on the magnetic field. The size of polar caps depends on the field
d accretion rate: ~ $R\,(R/R_A)^{1/2}$

gnetic fields

ry uncertain, as models of the field decay cannot give any solid predictions
very long time scales (billions of years).

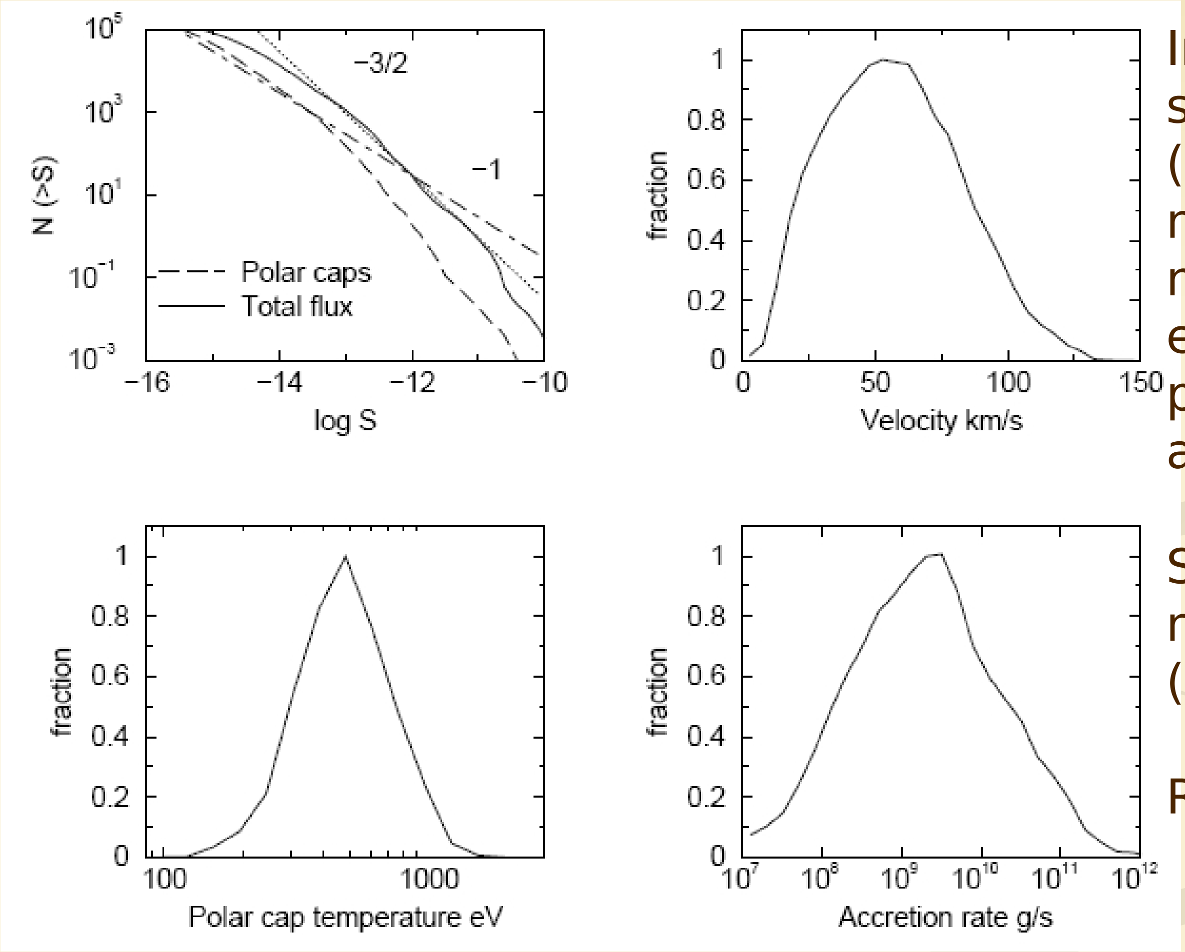
ux variiability.

e to fluctuations of matter density and turbulent velocity in the ISM
expected that isolated accretors are variable on a time scale
$_G$/v ~ days - months

---

l, isolated accretors are expected to be numerous at low fluxes
eir total number in the Galaxy is large than the number of coolers
comparable luminosity). They should be hotter than coolers, and
ve much longer spin periods.

Properties of accretors



In the framework of a simplified model (no subsonic propeller, no field decay, no accretion inhibition, etc.) one can estimate properties of isolated accretors.

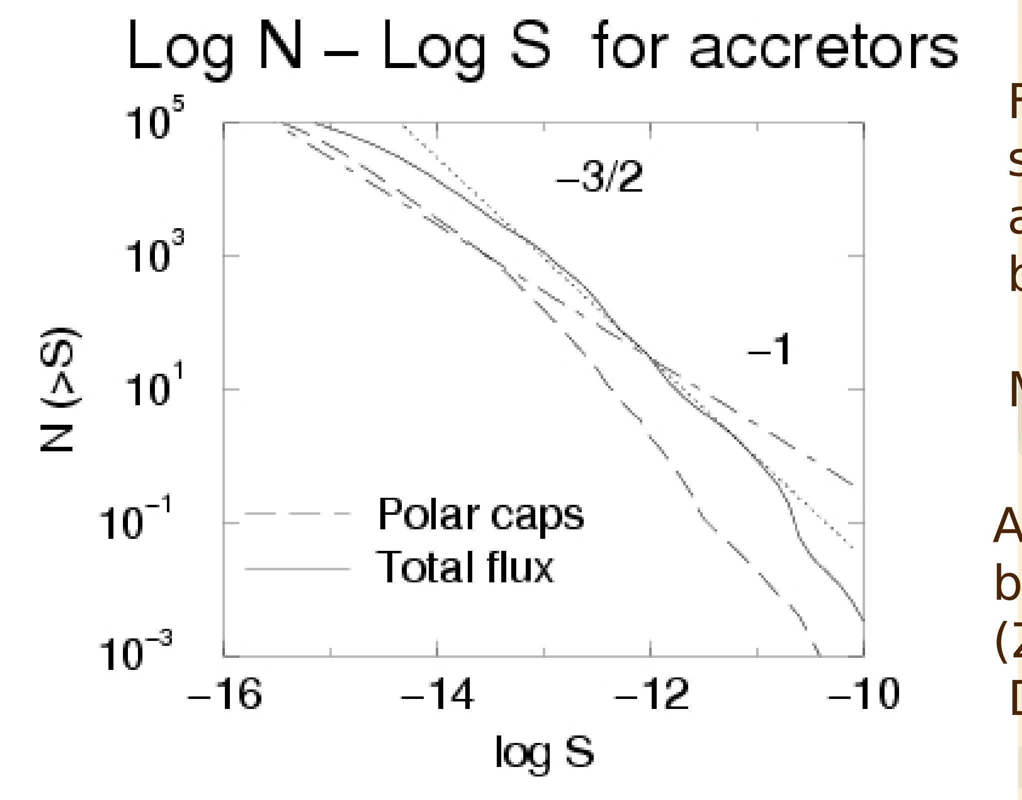
Slow, hot, dim, numerous at low fluxes ($<10^{-13}$ erg/cm^2/s)

Reality is more uncertain.

(astro-ph/0009225)

Accreting isolated NSs

mall fluxes $<10^{-13}$ erg/s/cm^2 accretors can become more abundant
n coolers. Accretors are expected to be slightly harder:
-500 eV vs. 50-100 eV. Good targets for eROSITA!



From several hundreds up to several thousands objects at fluxes about few $\cdot 10^{-14}$, but difficult to identify.

Monitoring is important.

Also isolated accretors can be found in the Galactic center (Zane et al. 1996, Deegan, Nayakshin 2006).

astro-ph/0009225

Where and how to look for

sources are dim even in X-rays,
d probably are extremely dim in other bands
s very difficult to find them.

otimistic scenario they outnumber cooling NSs at low fluxes.
y, for ROSAT they are to dim.
e that eROSITA will be able to identify accreting INSs.

patial density at fluxes ~10^{-15} erg/cm^2/s is expected to be ~few per sq.degree
tions close to the galactic plane.

cessary to have an X-ray survey at ~100-500 eV with good resolution.

ent paper by Muno et al.the authors put interesting limits on the
r of nidentified magnetars. The same results can be rescaled to
nits on the M7-like sources.

The isolated neutron star candidate 2XMM J104608.7-594306

A new INS candidate:

B >26, *V* >25.5, *R* >25
(at 2.5σ confidence level)

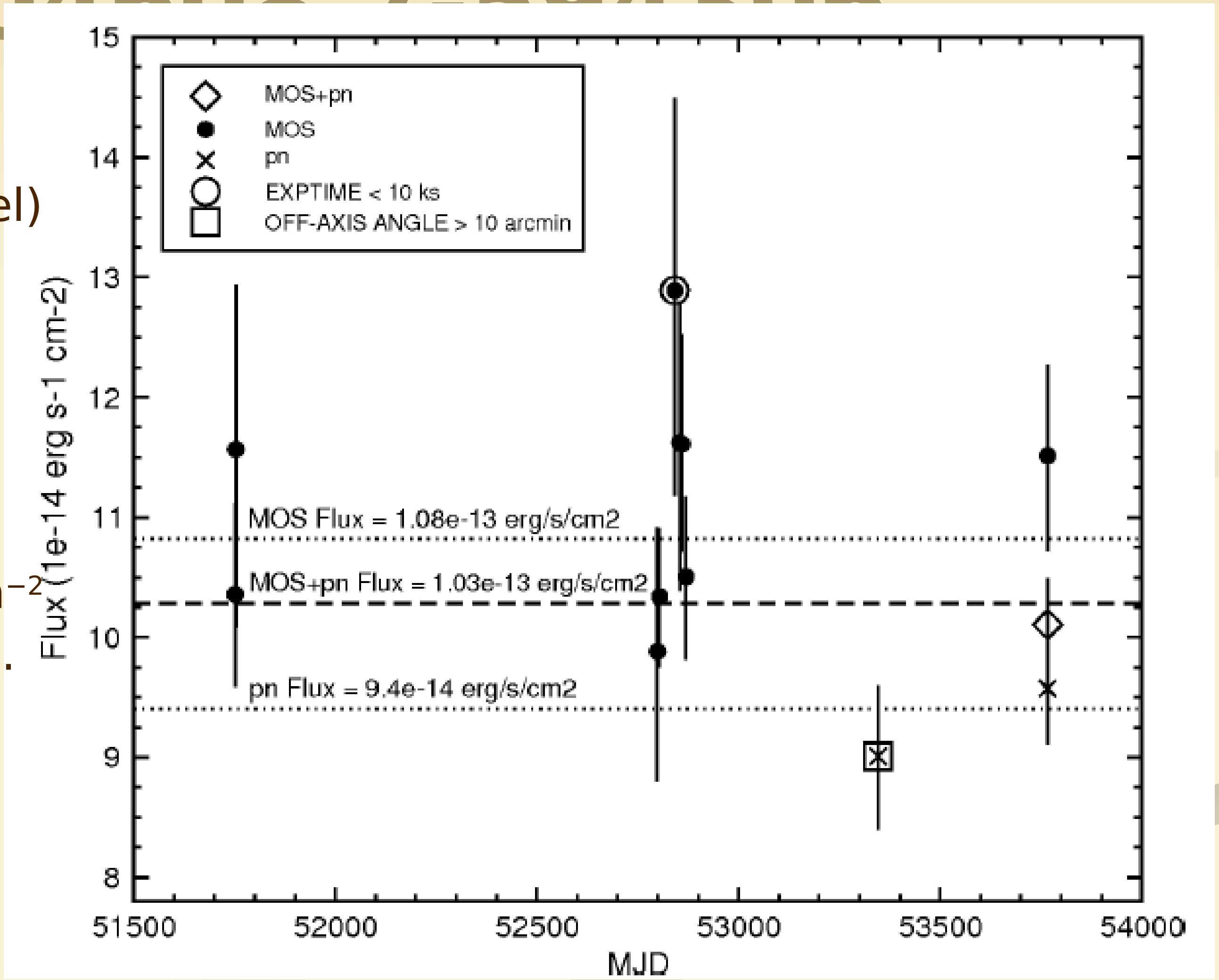
$\log(F_X/F_V) > 3.1$

kT = 118 +/-15 eV

unabsorbed X-ray flux:
$F_x \sim 1.3\ 10^{-12}$ erg s^{-1} cm^{-2}
in the 0.1–12 keV band.

At 2.3 kpc (Eta Carina)
the luminosity is
$L_X \sim 8.2\ 10^{32}$ erg s^{-1}
$R_\infty \sim 5.7$ km

ICoNS???

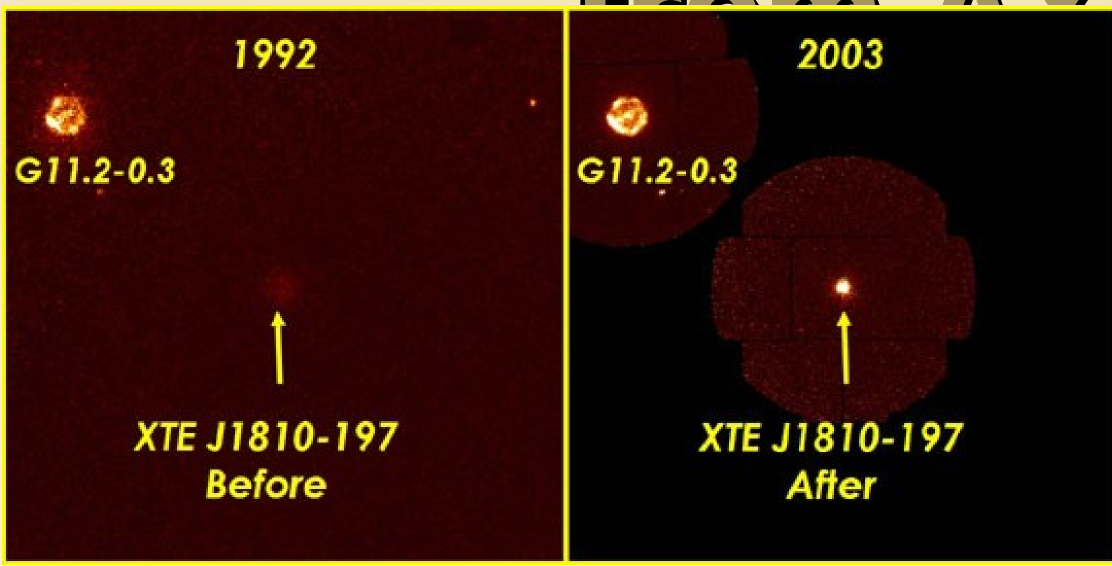


[Pires & Motch arXiv: 0710.5192 and Pires

Conclusions

s and M7, being the brightest (hottest) sources at the
follow different cooling tracks due to different compo
uter layers, or due to additional heating in the case o
netic field decay can be important even for the M7.
must be different from high-B pulsars.
eting INS are very important sources for understandi
magneto-rotational evolution.

Transient radio emission from AXP

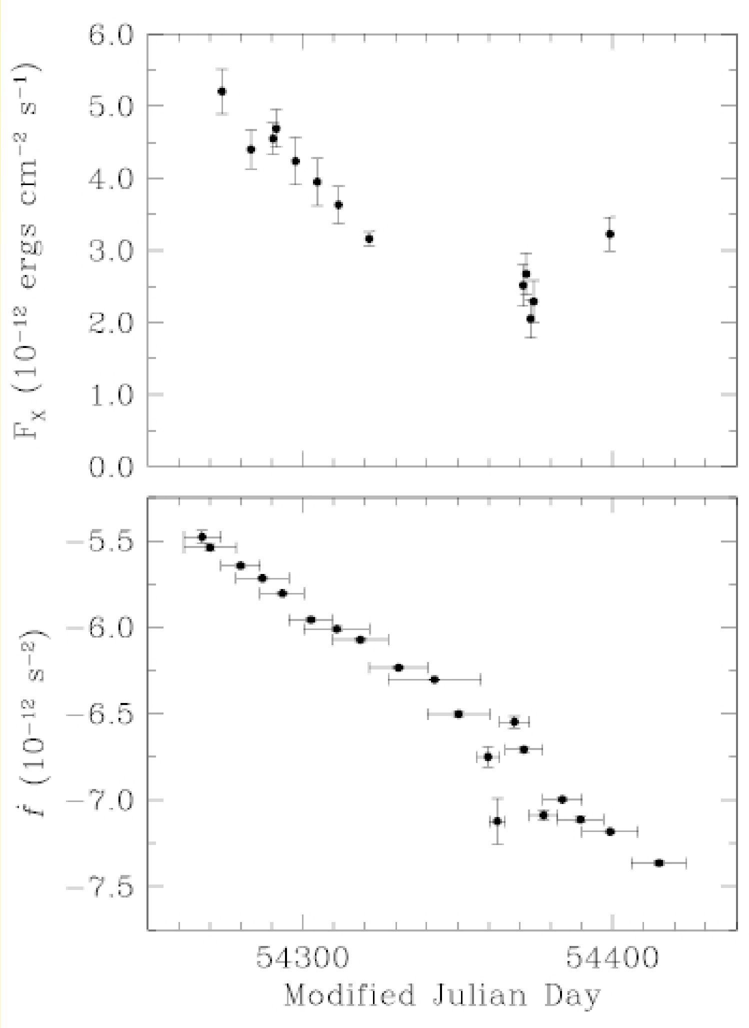


adio emission was detected from XTE 1810-197
uring its active state.

ne another magnetar was reported to be detected
t low frequencies in Pushchino, however, this result
as to be checked.

(Camilo et al. astro-ph/0605429)

Another AXP detected in radio



1E 1547.0-5408
P= 2 sec
SNR G327.24-0.13

arxiv:0711.3780, 0802.0494