On the (lack of) binary magnetars

Sandro MEREGHETTI
INAF – IASF Milano

Outline

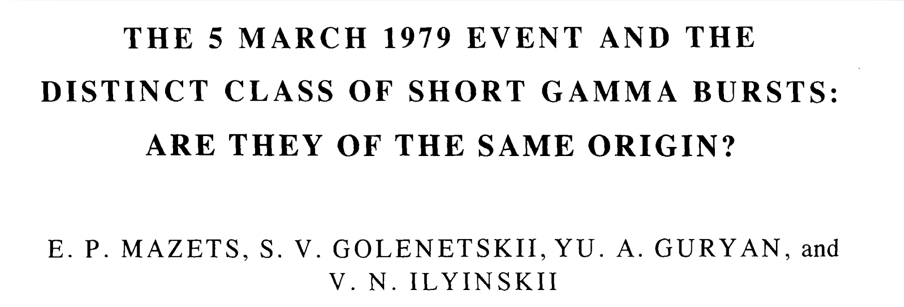
1. Introduction

2. How many magnetars ?

3. Isolated wrt binary magnetars

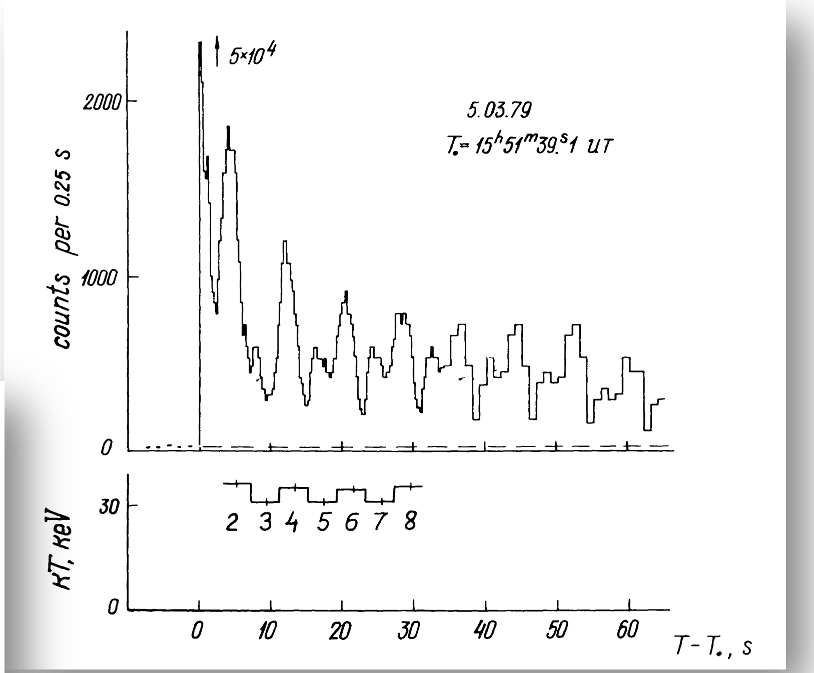
Soft Gamma-ray Repeaters

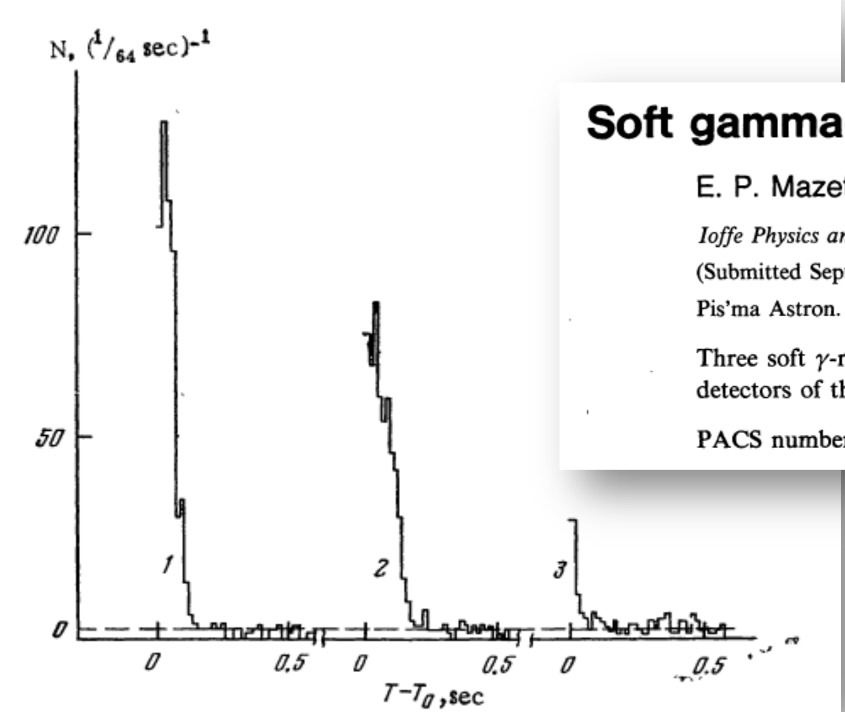
Discovered in 1979 as **transient** sources of hard X-ray bursts and giant flares (GF)



THE 5 MARCH 1979 EVENT AND THE DISTINCT CLASS OF SHORT GAMMA BURSTS: ARE THEY OF THE SAME ORIGIN?

E. P. MAZETS, S. V. GOLENETSKII, YU. A. GURYAN, and V. N. ILYINSKII





Soft gamma-ray bursts from the source B1900+14

E. P. Mazets, S. V. Golenetskii, and Yu. A. Gur'yan

Ioffe Physics and Technology Institute, USSR Academy of Sciences, Leningrad

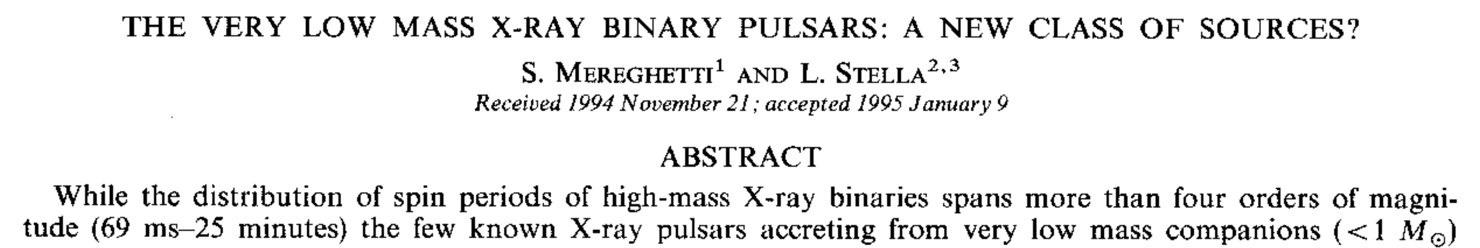
(Submitted September 11, 1979)
Pis'ma Astron. Zh. **5**, 641–643 (November–December 1979)

Three soft γ-ray bursts from the same source were recorded on 1979 March 24, 25, and 27 by the γ-ray detectors of the Cone experiment aboard the Venera 11 and Venera 12 space probes.

PACS numbers: 97.60.Gb, 98.70.QY

Anomalous X-ray Pulsars

Identified in the 90’s as a class of **persistent** X-ray pulsars with no signs of binary companions and $L_x >> dE_{rot}/dt$



THE VERY LOW MASS X-RAY BINARY PULSARS: A NEW CLASS OF SOURCES?

S. MEREGHETTI[1] AND L. STELLA[2,3]

Received 1994 November 21; accepted 1995 January 9

ABSTRACT

While the distribution of spin periods of high-mass X-ray binaries spans more than four orders of magnitude (69 ms–25 minutes) the few known X-ray pulsars accreting from very low mass companions ($<1\ M_\odot$) have very similar periods between 5.4 and 8.7 s. These pulsars also display several other similarities, and we propose that they are members of a subclass of low mass X-ray binaries (LMXBs) with similar magnetic field

istories. If they are rotating at, or close to,

sities of the order of a few times 10^{35} ergs

ss of LMXBs characterized by lower lumi-

LMXBs.

tron — stars: rotation — X-rays: stars

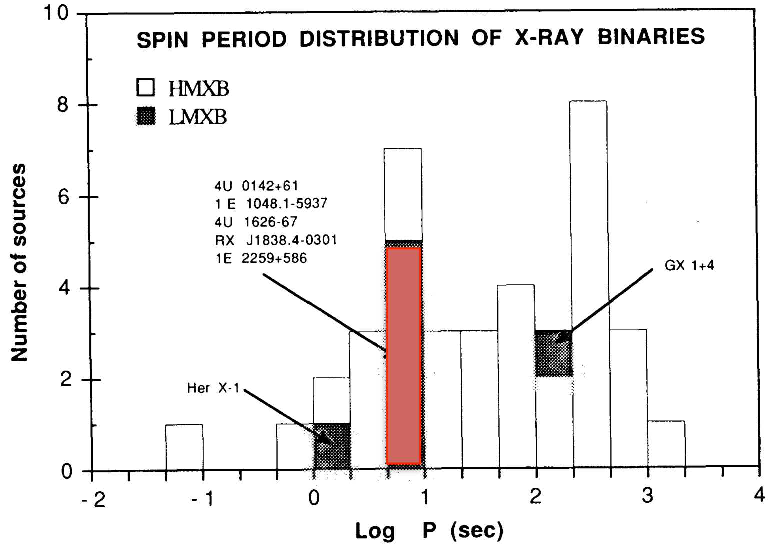
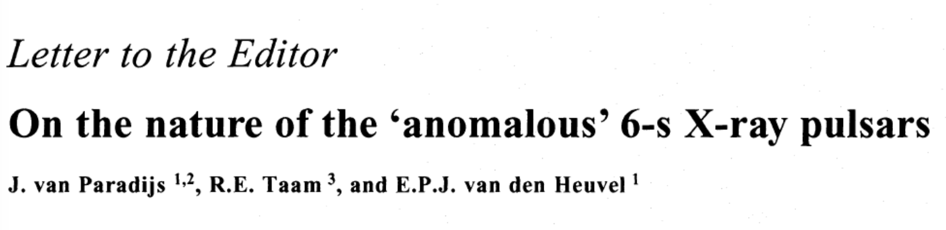


FIG. 1.—The distribution of the spin periods of accreting X-ray pulsars. With the exception of the peculiar systems Her X-1 and GX 1+4, the LMXBs X-ray pulsars have very similar periods between 5.4 and 8.7 s.



Letter to the Editor

On the nature of the ‘anomalous’ 6-s X-ray pulsars

J. van Paradijs [1,2], R.E. Taam [3], and E.P.J. van den Heuvel [1]

“Historically” two classes of sources:

See review Mereghetti 2008, Astr. & Astroph. Review 15, 225

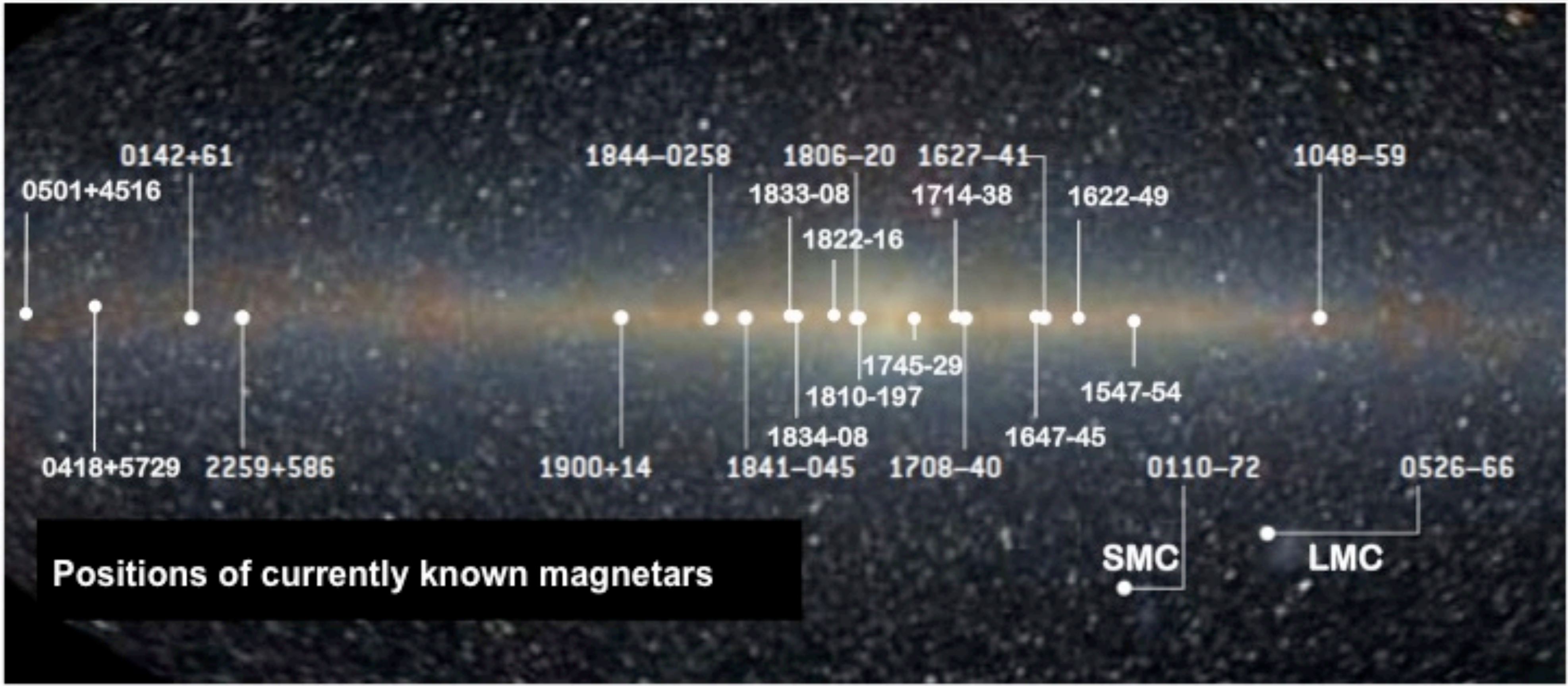
- **Soft Gamma-ray Repeaters**
  - Have X-ray counterparts showing all the properties of AXPs
- **Anomalous X-ray pulsars**
  - Most of them emitted “SGR-like” bursts

Generally believed that

AXPs = SGRs = (candidate) magnetars

Magnetar model: Paczynski 1992
Thompson , Duncan 1992, 1993, 1995 , 1996, ..
Beloborodov+ 2007, 2009, 2011, 2013, 2015, …
Lyutikov , Kulkarni, Heyl, Baring, …. and many others…

23 confirmed AXP/SGR in the Galaxy and Magellanic Clouds



NAME	P (s)	ASSOCIATIONS	RADIO	IR	OPTICAL	X SOFT	X HARD
CXO J0110-72	8.0	SMC				P	
4U 0142+61	8.7			D	P	P	P
1E 1048-59	6.4			D	P	P	D
1E 1547-54	2.1	G327.24-0.13	P	D		P T	P
CXO J1647-45	10.6	Westerlund 1				P T	
RXS 1708-40	11.0			D?		P	P
XTE J1810-197	5.5		P	D		P T	
1E 1841-045	11.8	Kes 73		D?		P	P
1E 2259+586	7.0	CTB 109		D		P	
SGR 0501+45	5.7			D	P	P T	P
SGR 0526-66	8	LMC , N49				P	
SGR 1627-41	2.6					P T	
SGR 1806-20	7.6	Star cluster	T	D		P	D
SGR 1900+14	5.2	Star cluster	T	D?		P	D
SGR 0418+57	9.1					P T	
PSR J1622-49	4.3	SNR ? G333.9+0.0	P		P	P T	
CXO J1714-38	3.8	CTB 37B				P	
Swift J1822-16	8.4					P T	
SGR 1833-08	7.6					P T	
Swift J1834-08	2.5	W41 ?				P T	
SGR 1745-29	3.8	0.1 pc from Gal.Center	P			P T	P
3XMM 1852	11.6					P T	
SGR J1935+21	3.25	G57.2+0.8				P T	

Outline

1. Introduction

2. How many magnetars ?

   Many more than the observed ~23 :

   1. Transients

More than half of the currently known AXPs/SGRs are transients

- **Outbursts**
  last weeks-months, often associated with emission of hard X-ray bursts.

  → easy to detect

- **Quiescent periods**
  lasting many years at much lower luminosity (10^{31}-10^{32} erg/s), without distinctive signatures

  → difficult to detect/ recognize

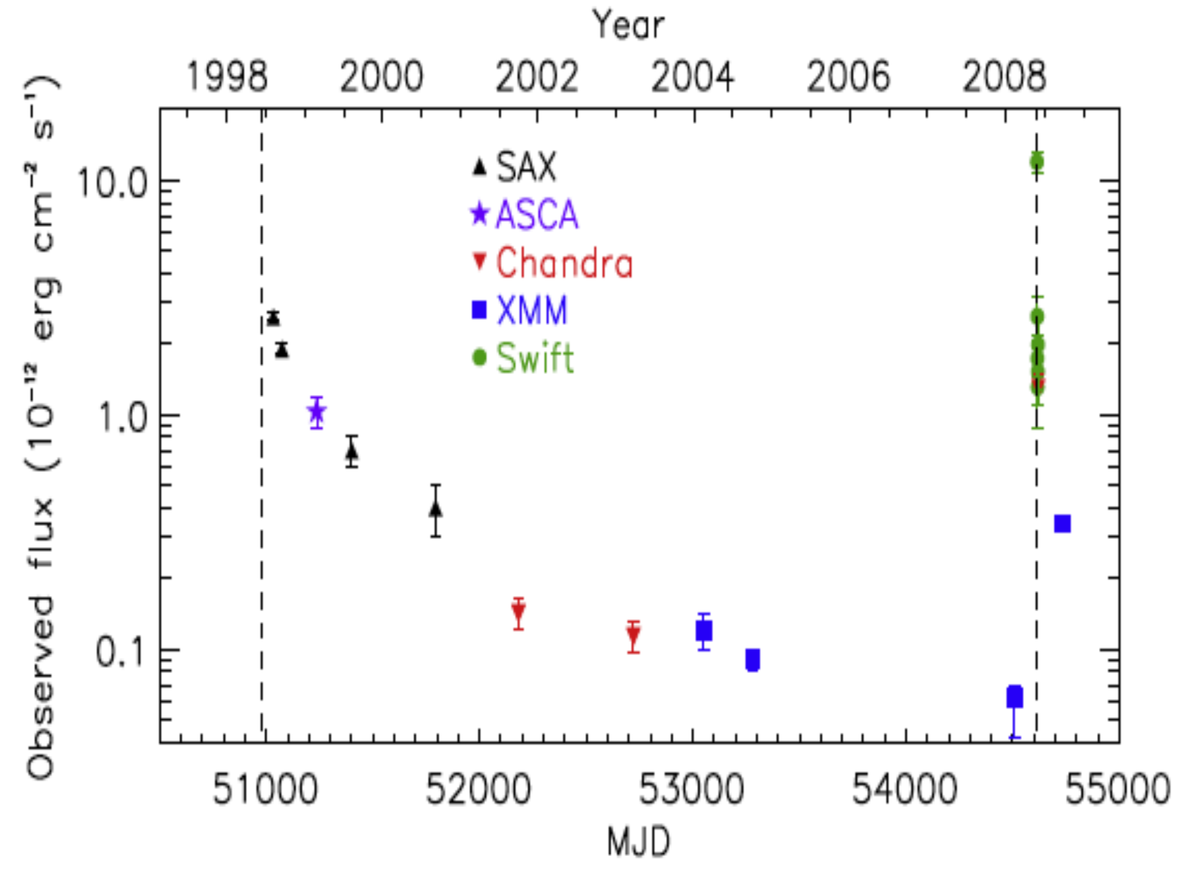
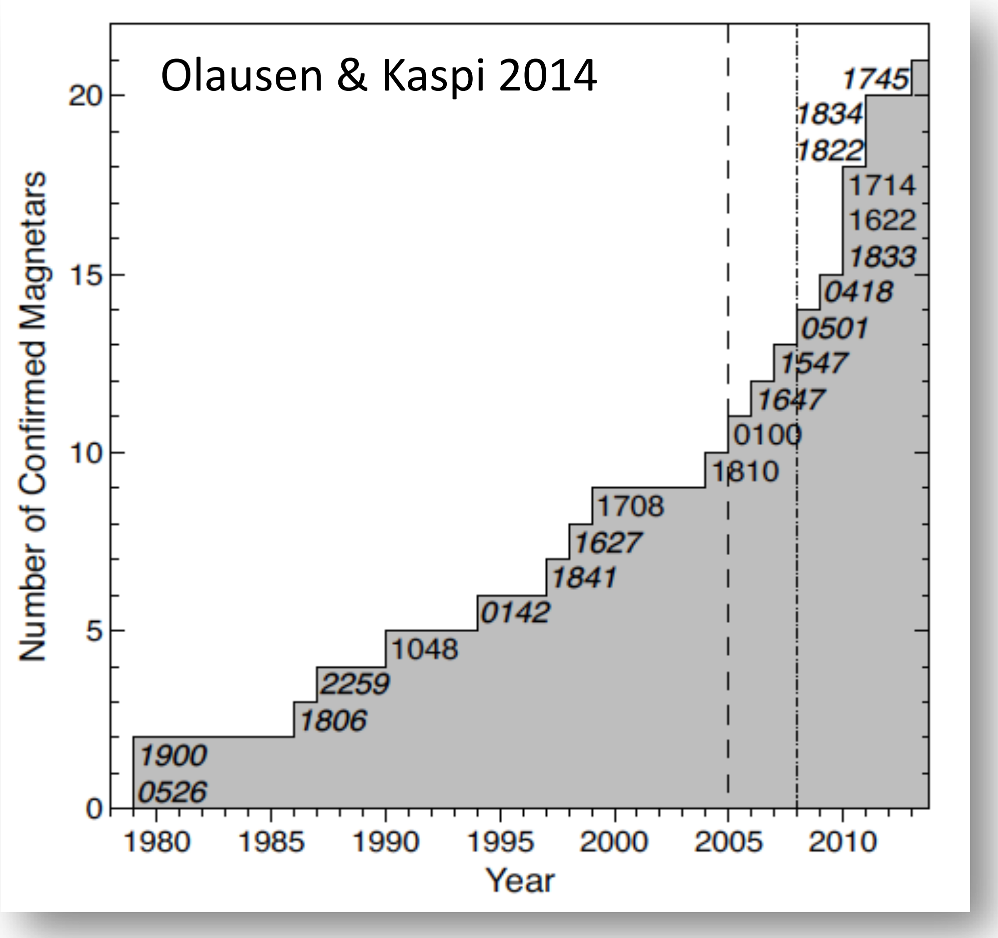


Fig. 1. (From Esposito et al. (2008).) X-ray light curve of SGR 1627–41

More than half of the currently known AXPs/SGRs are transients

… and their number will grow

- ~all the AXPs/SGRs discovered in last 10 yrs are transients
- Most of them seen in outburst only once
- Muno+ 2008 estimate ~30÷150 persistent AXPs and up to ~1000 transient magnetars in the Galaxy yet to be discovered



Olausen & Kaspi 2014

Outline

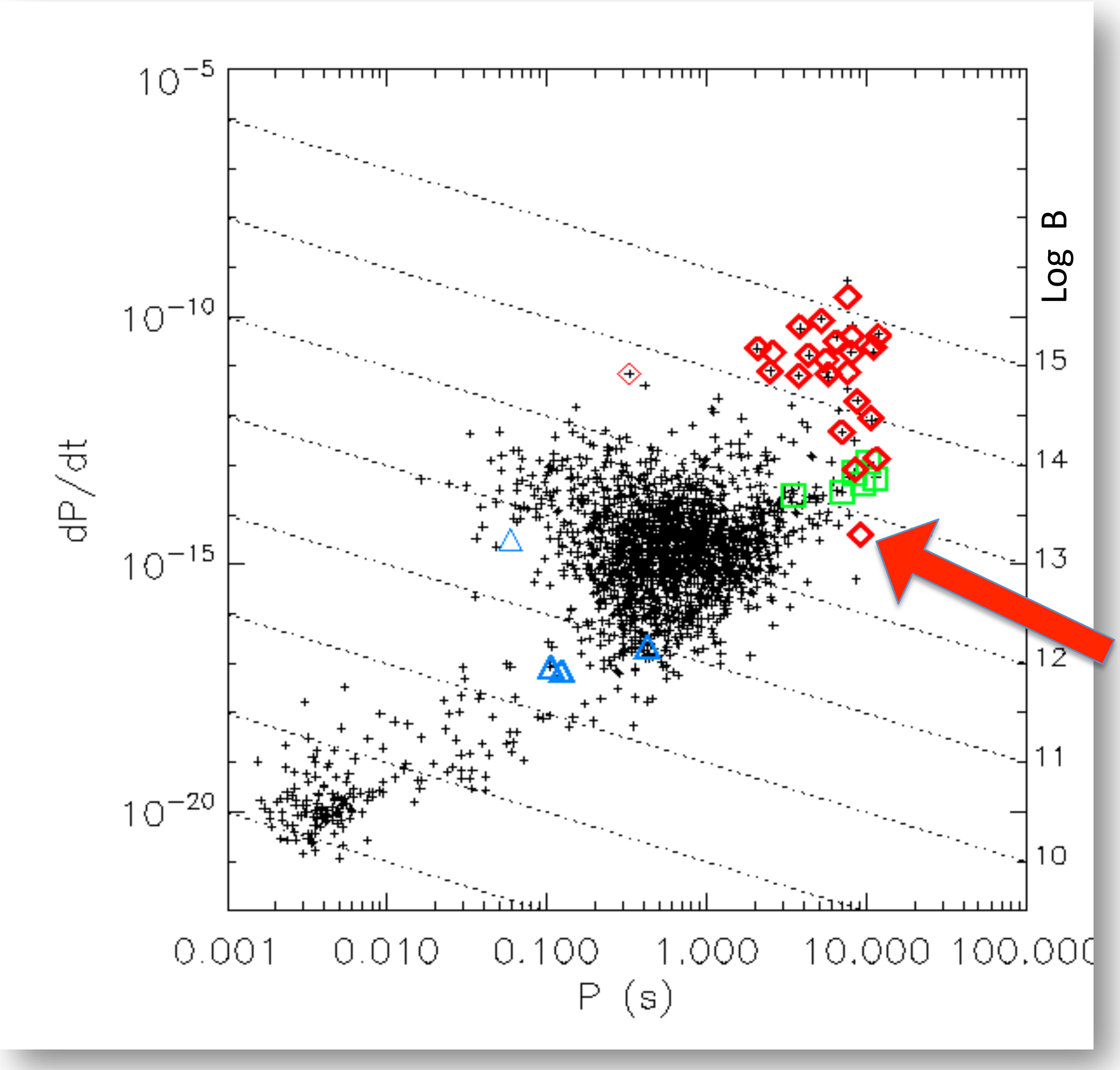
1. Introduction

2. How many magnetars ?

   Many more than the observed ~23 :

   1. Transients
   2. Low B magnetars (or, better, low P-dot magnetars)
   3. Magnetar-like activity from rotation-powered pulsars

Low P-dot magnetars



$$\frac{dE_{rot}}{dt} = 4\pi^2 I\dot{P}/P^3$$

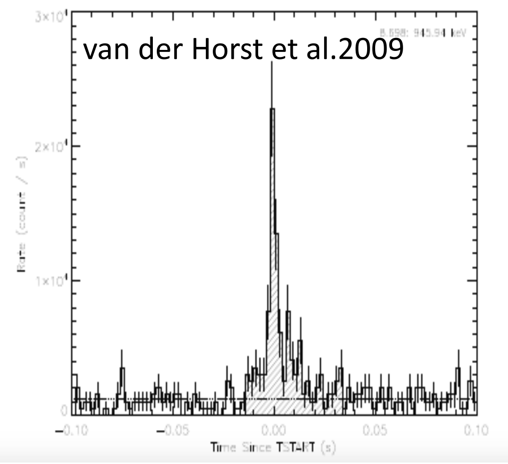
$$\frac{dE}{dt} = \frac{1}{6c^3}B^2R^6\omega^4 sin^2\alpha$$

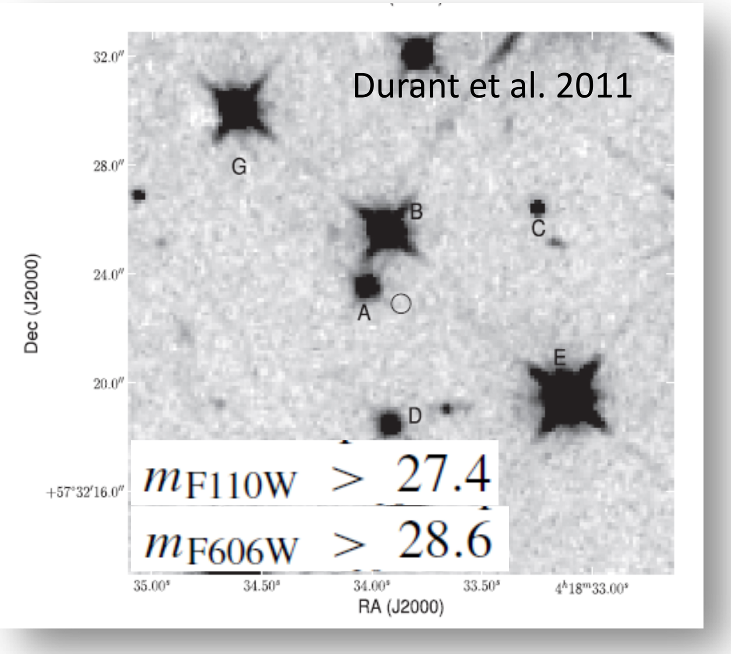
$$B = 3.2\cdot 10^{19}\sqrt{P\dot{P}}\ \text{Gauss.}$$

SGR 0418+5729
The magnetar with the smallest Pdot

Low P-dot magnetars: SGR 0418+5729

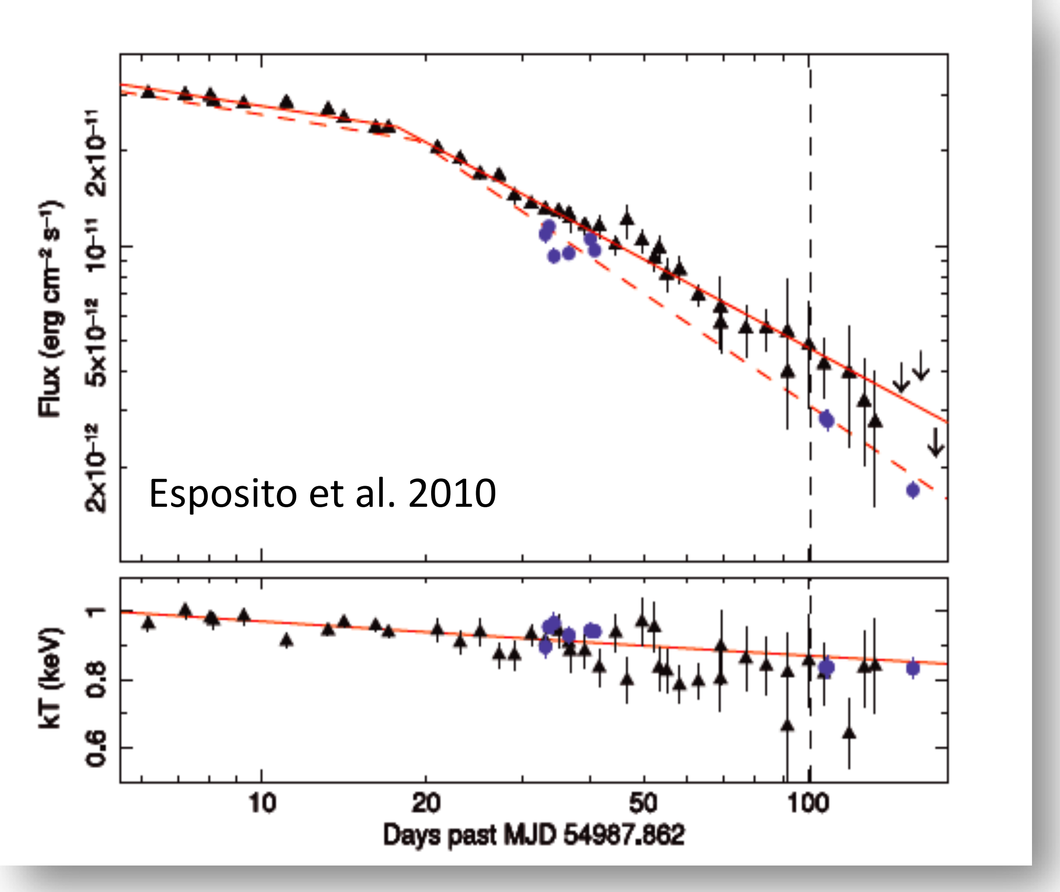
- two **BURSTS** detected on 2009 June 5
- spin **PERIOD** of 9.1 s (*van der Horst et al. 2010*)
- apparently all the features of a (transient) **SGR**
  - Rapid, large flux increase and decay
  - Emission of bursts
  - Soft X-ray spectrum
- no optical counterpart
- **VERY SMALL** dP/dt = 4×10^{-15} s s^{-1}


van der Horst et al.2009


Durant et al. 2011

$m_{\mathrm{F110W}} > 27.4$

$m_{\mathrm{F606W}} > 28.6$


Esposito et al. 2010

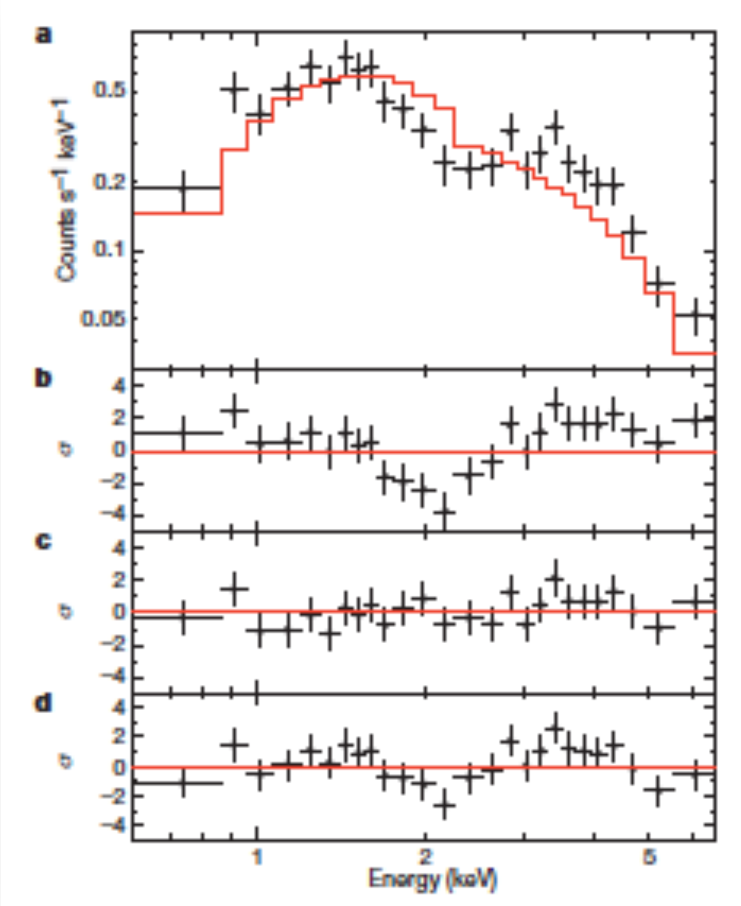
Low P-dot magnetars: SGR 0418+5729

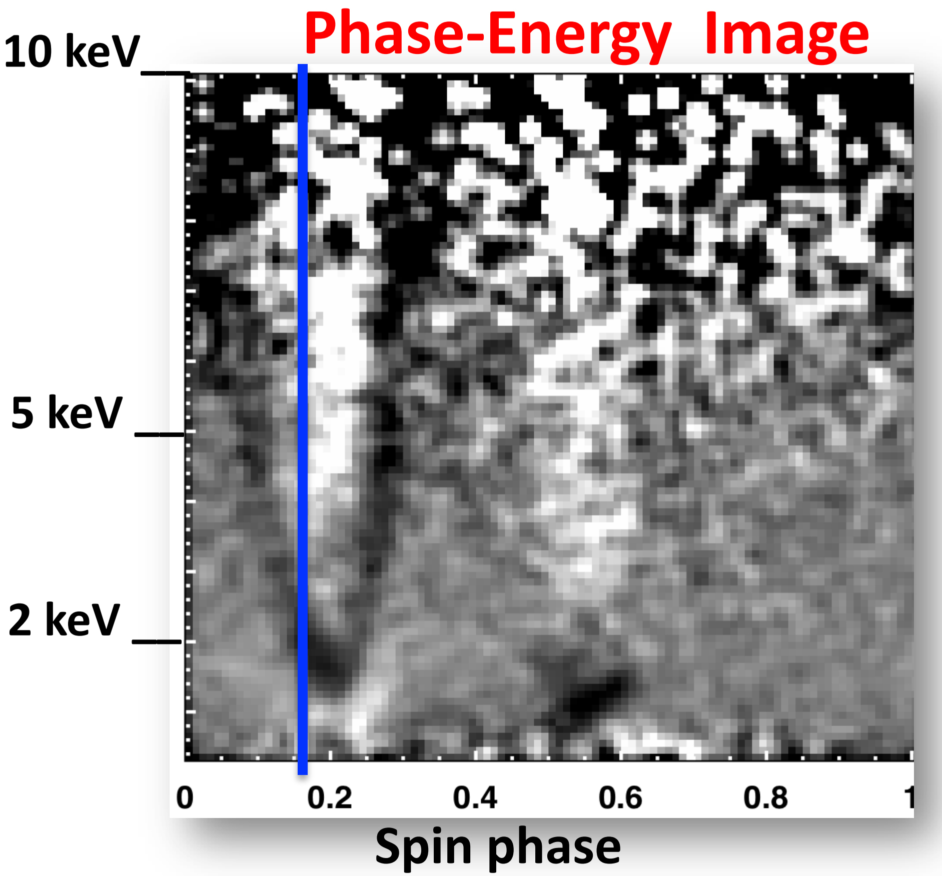
Discovery of absorption line at strongly phase-dependent energy

(Tiengo+ 2013, Nature)

Line energy varies between ~2 and ~10 keV as the star rotates by ~30-40° around its spin axis

Spectrum of 1/50 of phase

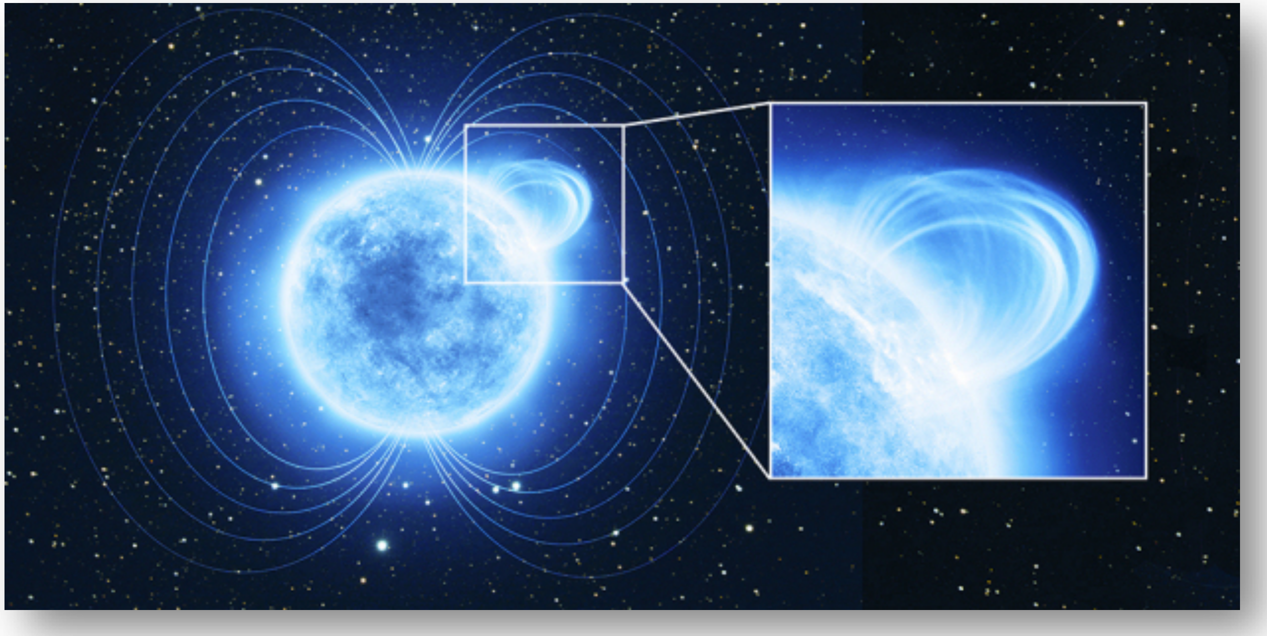


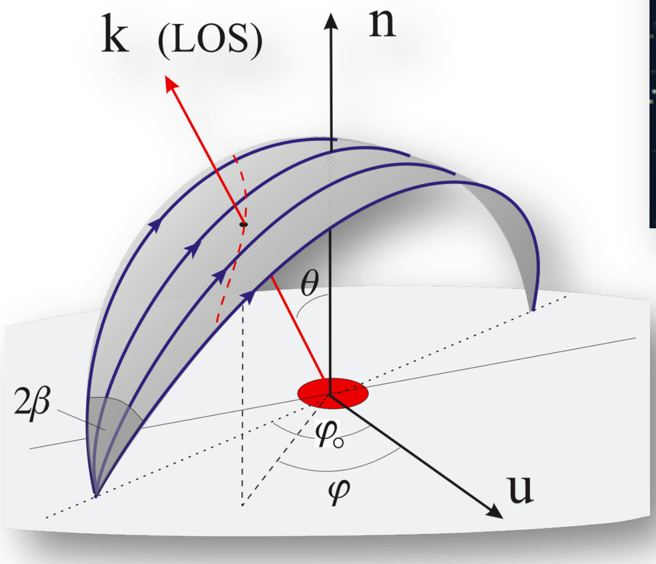

Phase-Energy Image

Low P-dot magnetars: SGR 0418+5729

Discovery of absorption line at strongly phase-dependent energy

(Tiengo+ 2013, Nature)



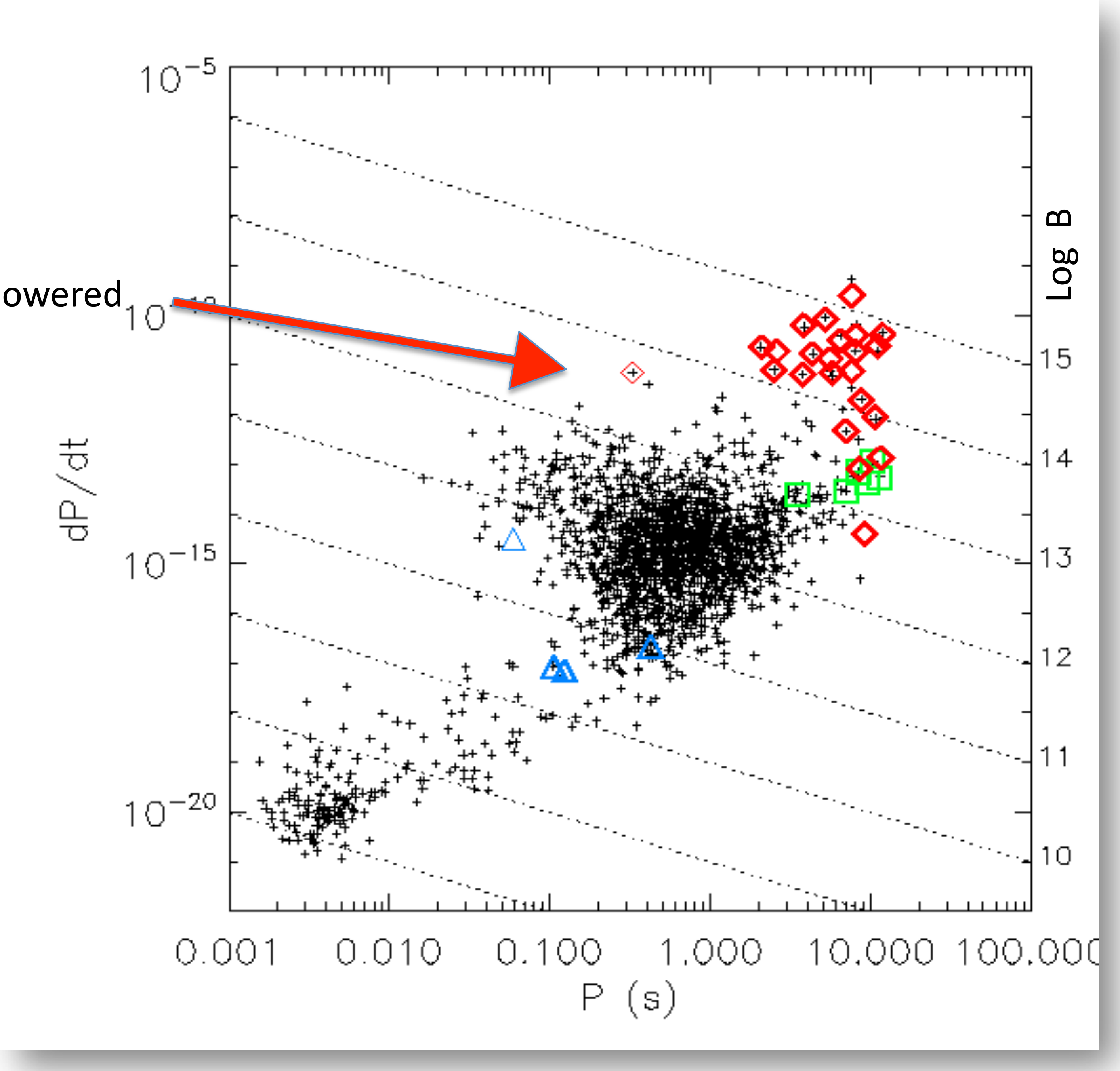


- cyclotron line from protons in small-scale loop with B from ≈2 10^{14} to ≈2 10^{15} G

- To be compared with the dipolar field B≈6 10^{12} G inferred from the timing parameters (Rea+ 2013)

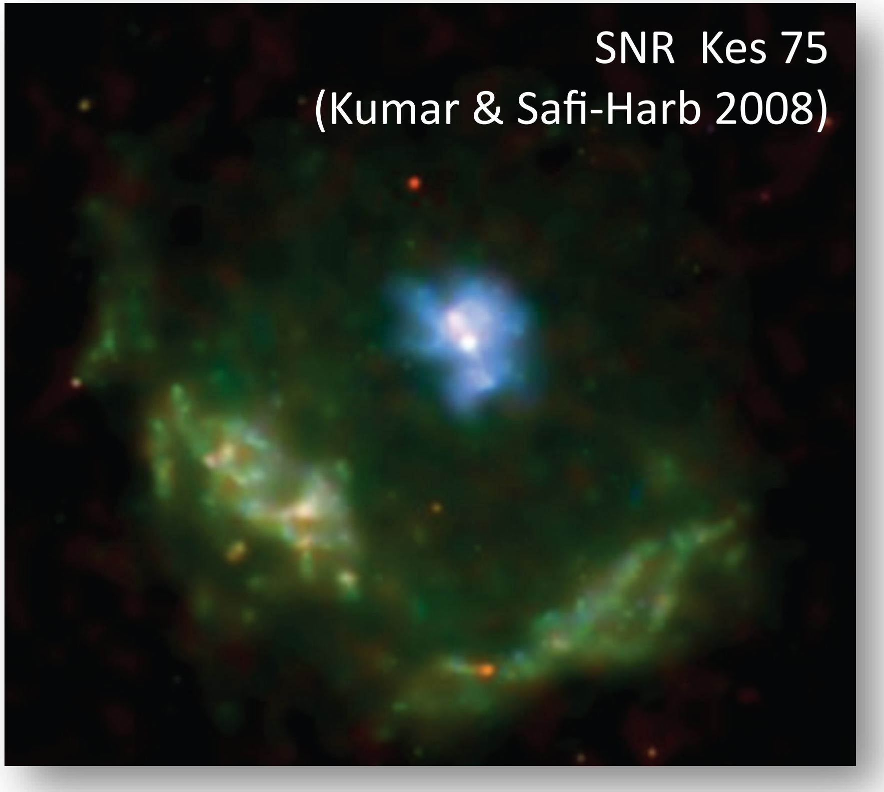
Low P-dot magnetars

PSR J1846-0258
An allegedly rotation-powered pulsar which showed magnetar-like activity



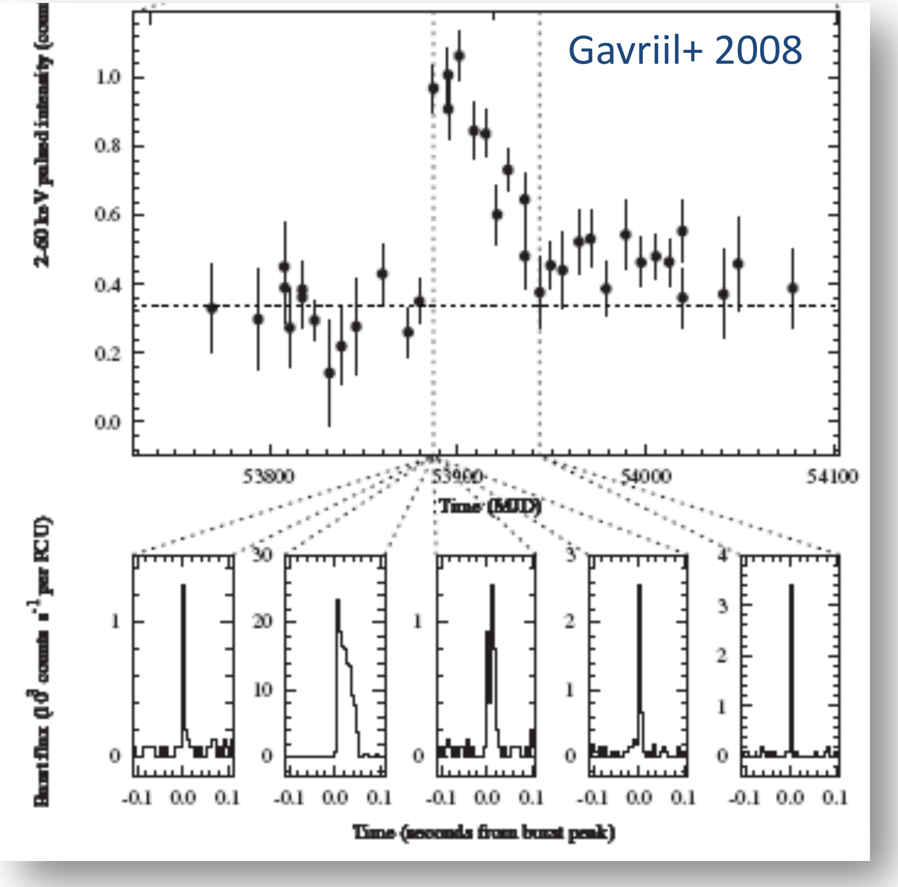
A rotation-powered PSR acting like a magnetar

PSR J1846-0258 in young SNR Kes75



SNR Kes 75

(Kumar & Safi-Harb 2008)



Gavriil+ 2008

$L_x = 4\ 10^{34}\ (d/6\ \mathrm{kpc})^2$ erg/s

$E_{rot} = 8\ 10^{36}$ erg/s

Outline

1. Introduction
2. How many magnetars ?
3. Isolated wrt binary magnetars

Popov & Prokhorov, 2006, MNRAS

- In 2005: “Among the dozen magnetar candidates there are no binary objects”
  - Large kick velocities
  - Specific evolutionary paths (e.g. leading to fast rotating stellar cores)

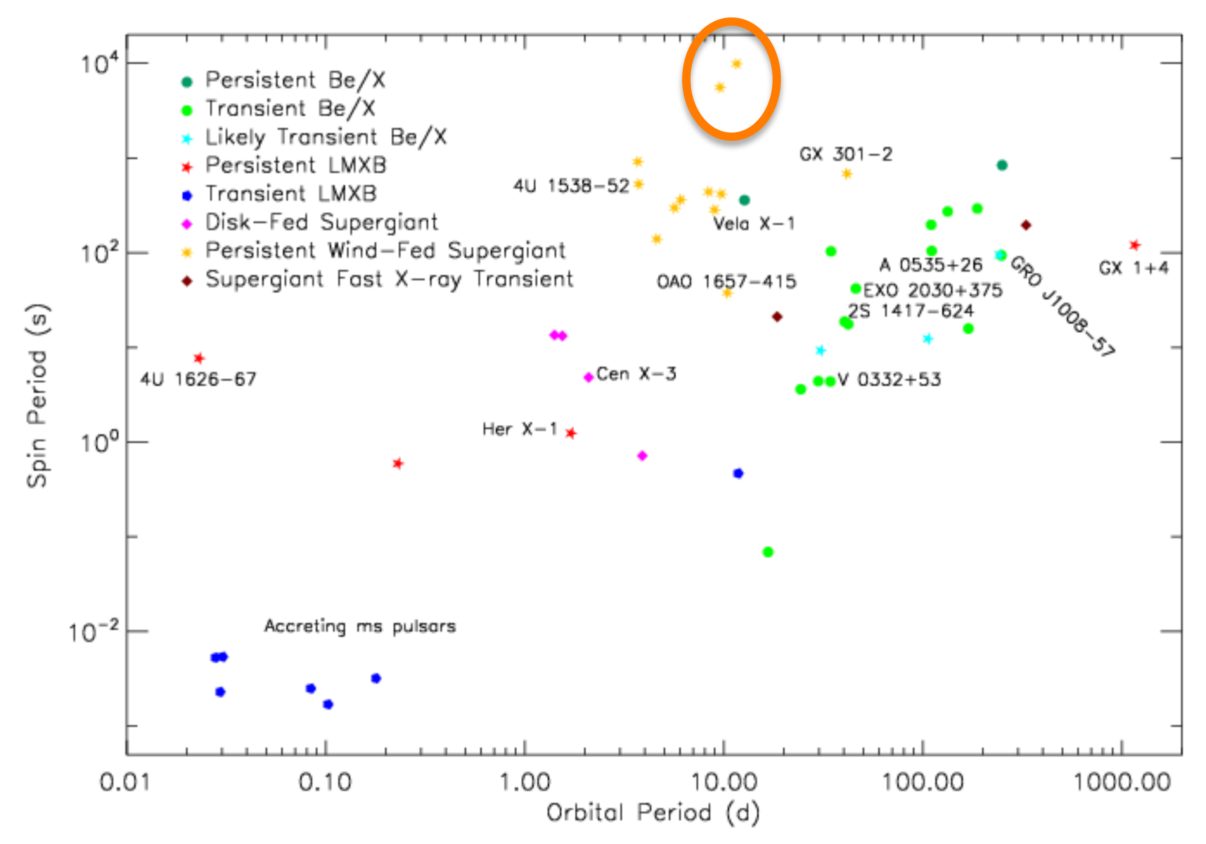
- Evolutionary calculations show that:
  - At most 8-9% of NS originate from systems with fast cores
  - However only ~1% of them remains in binary (due to coalescence or system disruption)

Proposed binary magnetars

- Long period pulsars in HMXRBs
- SuperGiant Fast X-ray Transients
- ULX transient in M82
- Peculiar γ-ray binary LS I +61° 303

Long spin-period pulsars in X-ray binaries

- Most accreting pulsars in HMXRBs have P_S ~ 1 – 1000 s
- A few of them, with long P_S, proposed as (former) magnetars, e.g.:
  - 2S0114+65 $P_S=10^4$ s (Li & van den Heuvel 1999)
  - 4U2206+54 $P_S=5560$ s (Finger+ 2010, Reig+ 2012)
  - SXP 1062 in SMC SNR $P_S=1062$ s (Popov & Turolla 2012)



Two possibilities:

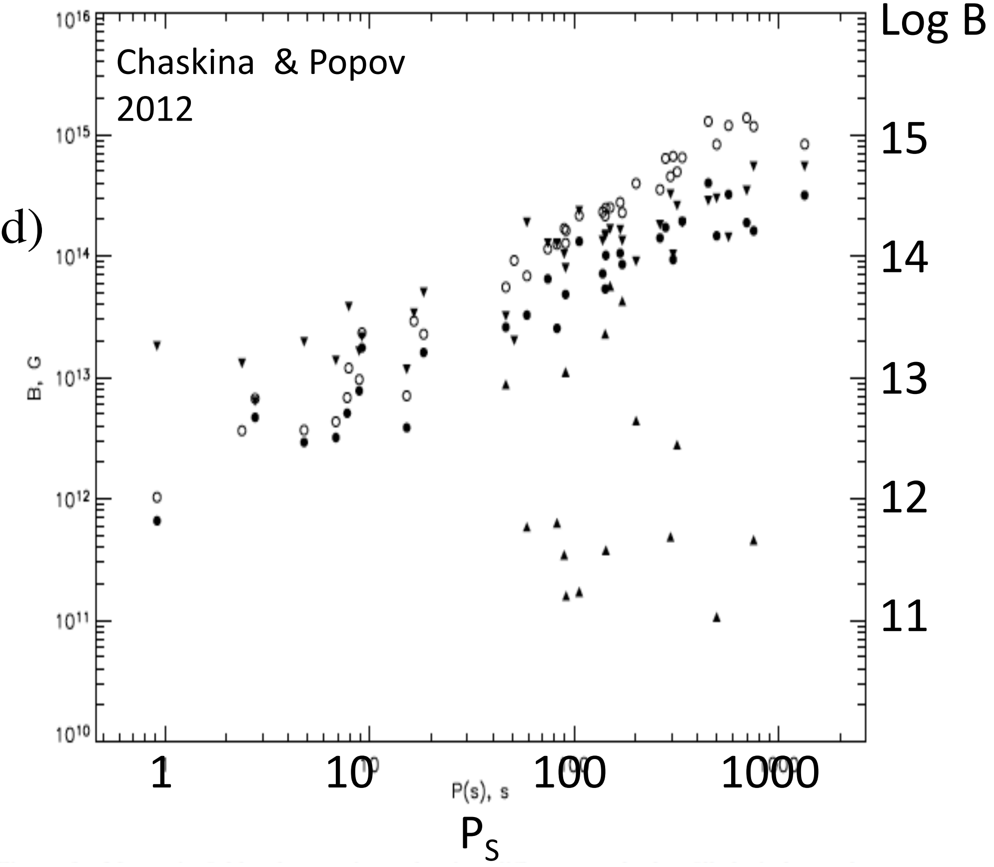
1. Ps is the current equilibrium period P_{EQ}
2. Ps reflects a previous evolutionary stage
   (i.e. P_S does not change much during X-ray active lifetime)

Long spin-period pulsars in X-ray binaries

1) P_S is the current equilibrium period P_{EQ}

$$P_{EQ} \sim 6 \;\; B_{12}^{6/7} \; \dot{M}_{16}^{-3/7} \quad \mathrm{s} \qquad\qquad \text{(disc)}$$

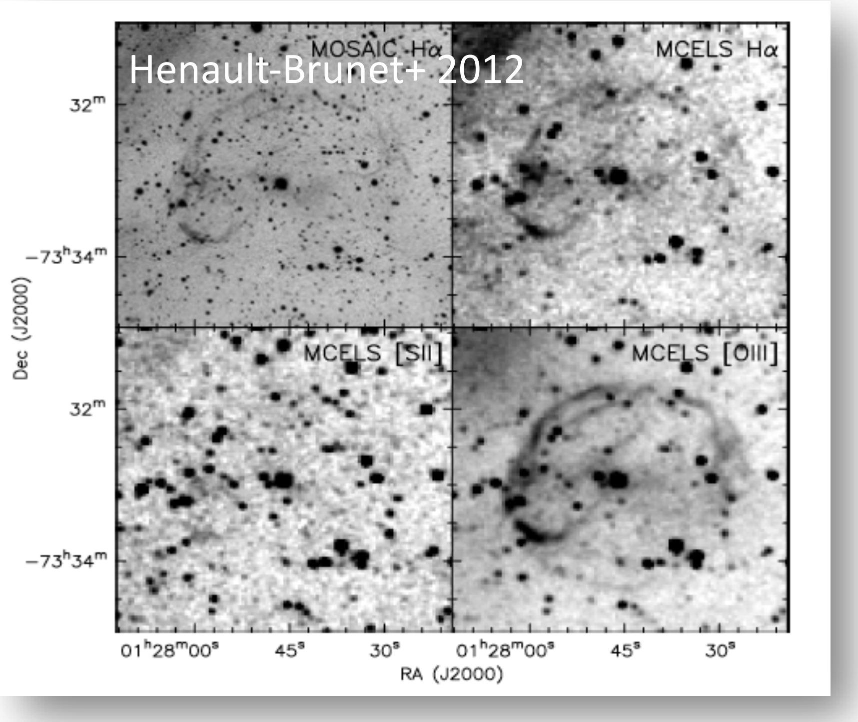
$$P_{EQ} \sim 50 \; P_{ORB,10d}^{1/2} \;\; B_{12} \; \dot{M}_{16}^{-1/2} \quad \mathrm{s} \quad \text{(wind)}$$



Long spin-period pulsars in X-ray binaries

2) P_S reflects a previous evolutionary stage

Magnetized NS born with short P → **Ejector** spin-down → **Propeller** spin-down → **Accretor** alternates spin-up/down


Henault-Brunet+ 2012

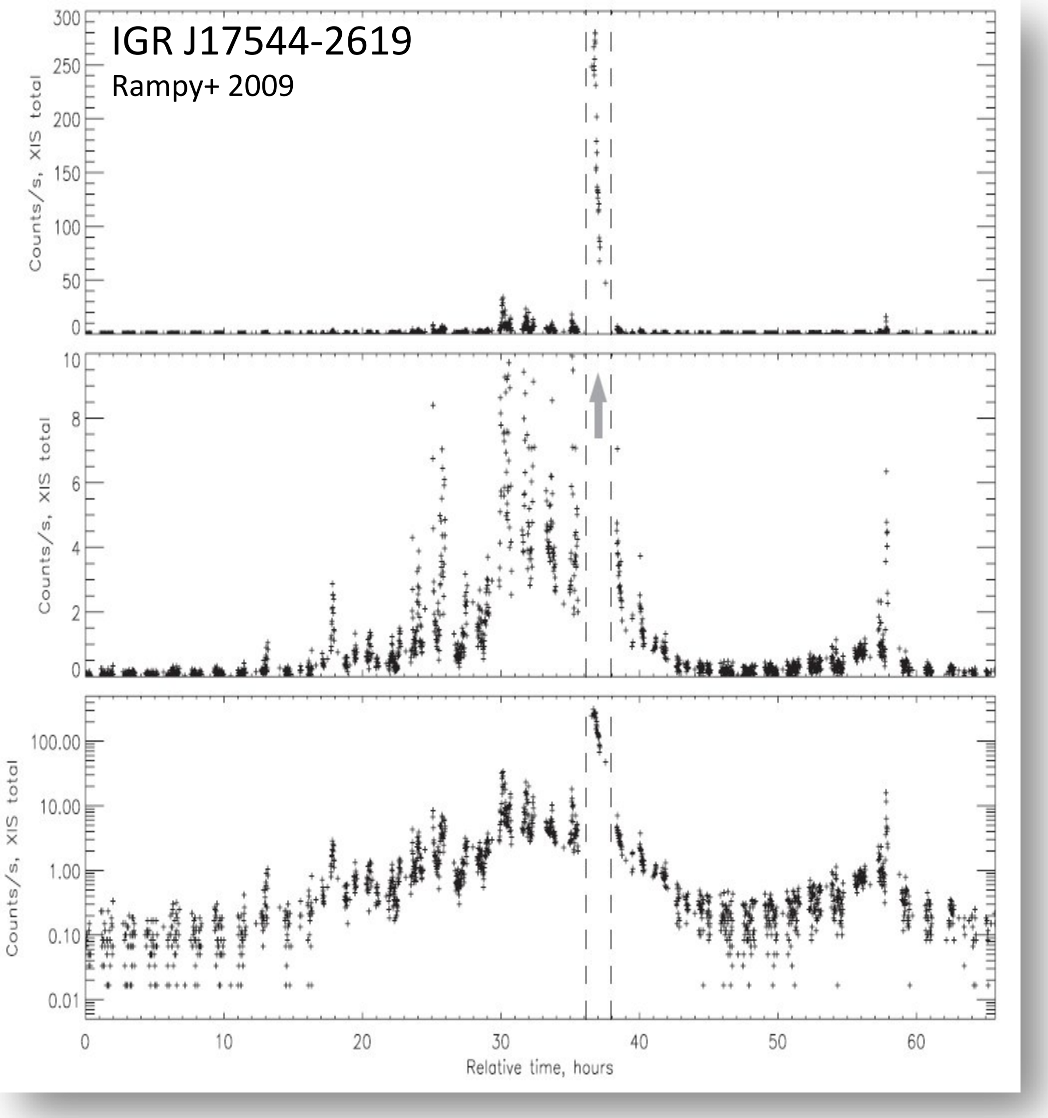
Be X-ray pulsar in the SMC with P_S=1062 s

associated with a young SNR (<40 kyrs)

Not enough time to slow down during the ejector phase unless initial $B > 10^{14}$ G (Popov & Turolla 2012)

Supergiant Fast X-ray Transients

NS with OB supergiant companions characterized by short (<~hours) outbursts with large (>10^4) dynamic range (review in Sidoli 2013)



One possible explanation in terms of magnetic gating mechanism (Grebenev & Syunyaev 2007, Bozzo+ 2008)

centrifugal ($R_M>R_{CO}$) or magnetic ($R_M>R_{AC}$) barrier → Small variations in accretion rate cause transitions across different regimes

$P_S>1000$ s and B>~10^{14} G required

ULX transient in M82

$L_X \sim 10^{40}$ erg/s
$P_S = 1.37$ s
Orbital modulation at 2.5 days

Average spin-up = $-2\ 10^{-10}$ s/s

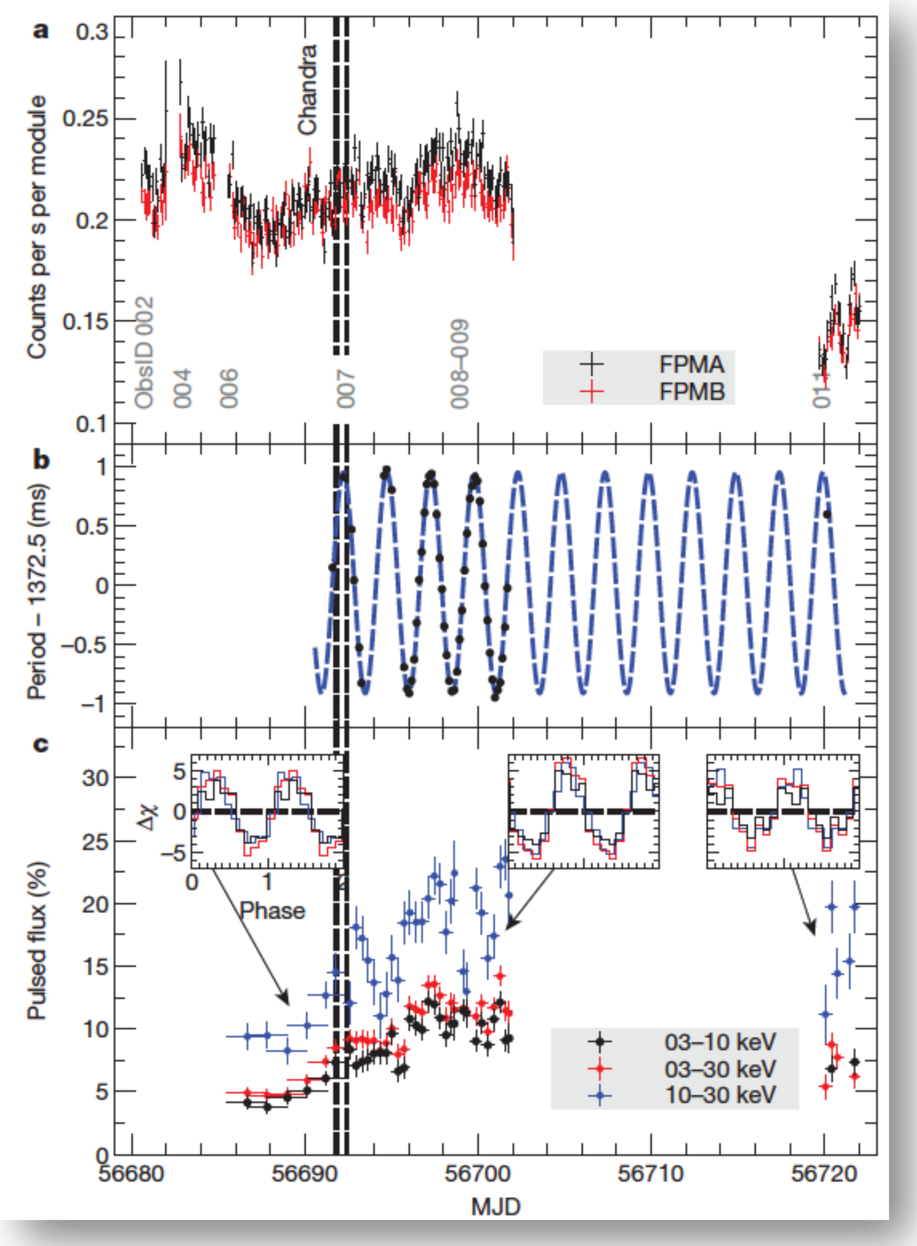
Eksi+ 2015 → $\sim 10^{14}$ G + stronger multipoles
($P \sim P_{EQ}$, disk accretion)

Lyutikov 2014 → $\sim 10^{13}$ G
(orthogonal rotator, accretion ''curtain'', small torque due to penetration of B field in accretion disk at $R > R_M$)

Tong 2015 → $\sim 10^{12}$ G + 10^{14} G multipoles
(beaming, disk accretion, massive NS, spin-up value)

Kluzniak & Lasota 2015 → $\sim 10^{9}$ G
(average spin-up, disk accretion)

Bachetti+ 2014, Nature

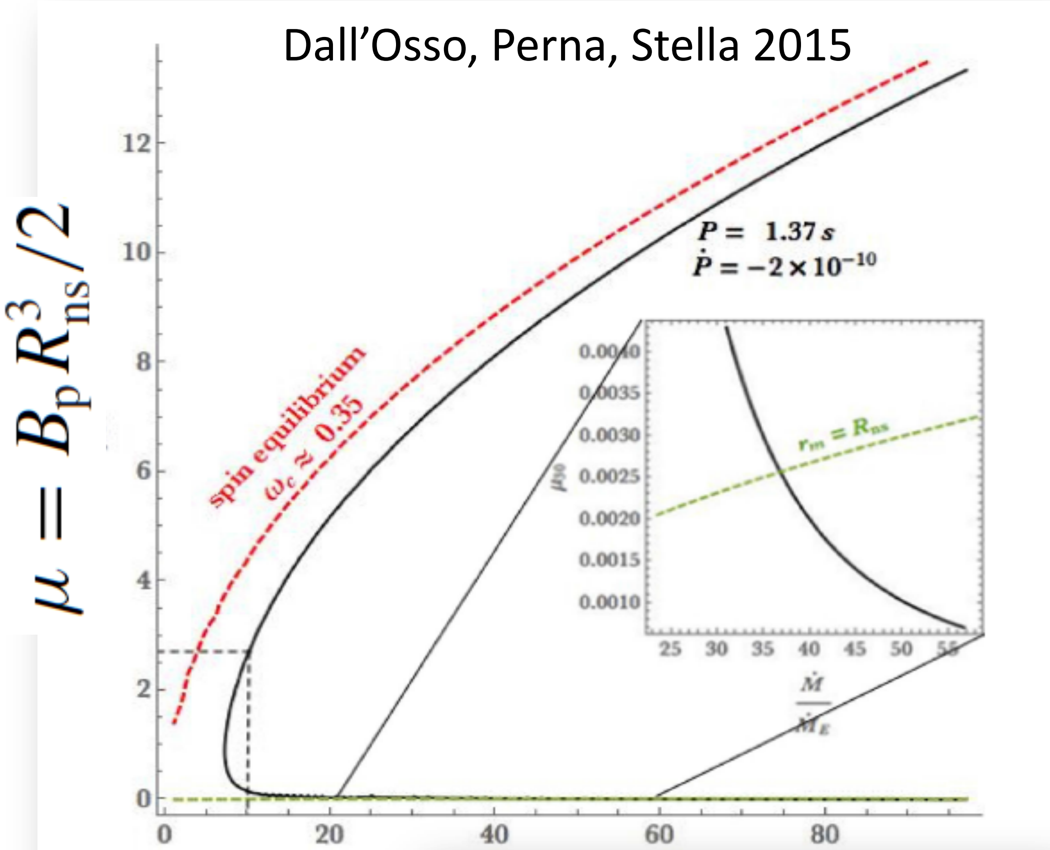


ULX transient in M82

Accretion disk with magnetic threading
(Ghosh&Lamb model)

Different combinations of accretion rate and magnetic field give the same torque

Observed variations in Pdot without large luminosity changes favor the High B solution → B ~10^{13} G


Dall'Osso, Perna, Stella 2015

$$\frac{\dot{M}}{\dot{M}_{\rm E}} \approx 60\,\frac{b}{\eta}\left(\frac{L_{\rm X,iso}}{10^{40}\ {\rm erg\ s^{-1}}}\right)$$

Proposed binary magnetars

- Long period pulsars in HMXRBs

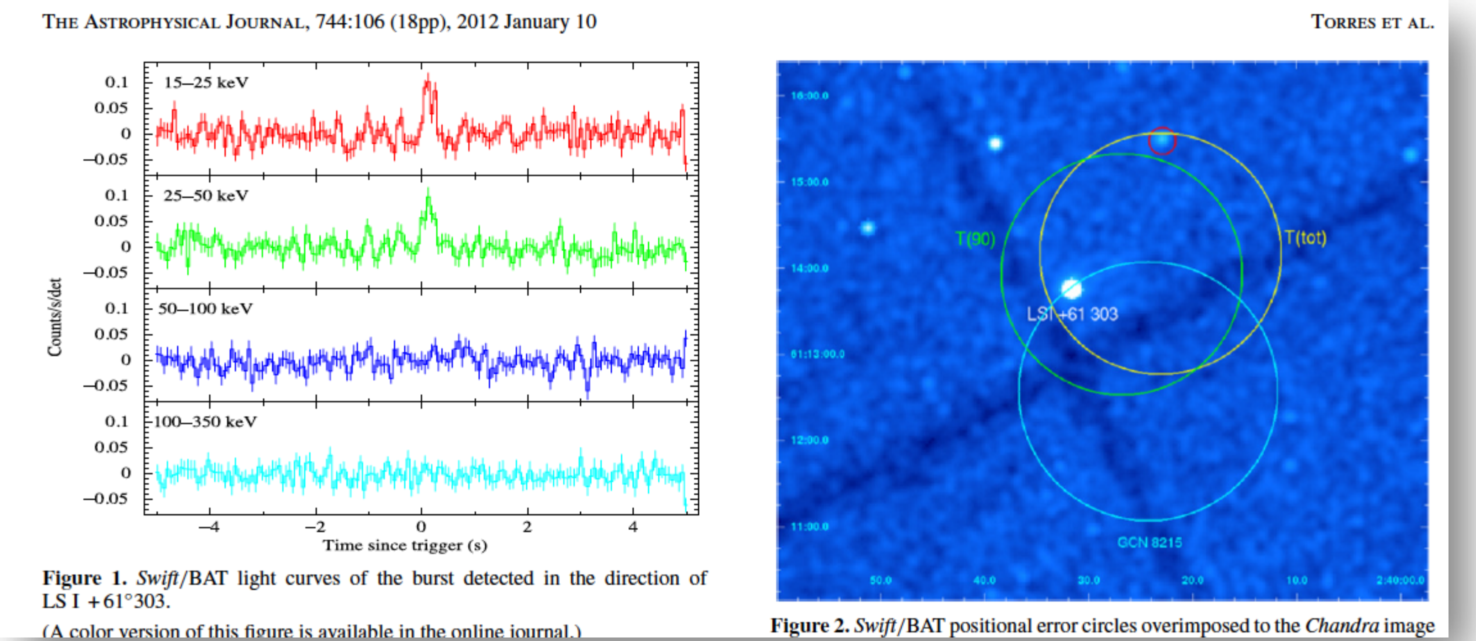
  SuperGiant Fast X-ray Transients

  ULX transient in M82
  - Model dependent: e.g. the details of interaction between accreting plasma and rotating magnetosphere
  - Uncertainties on Mdot estimated from L_X, distances
  - Cyclotron lines in these sources (including one SFXT) indicate ''canonical'' fields
  - SFXT do not have long spin periods
  - No other signs of "magnetar-like activity" in these sources
- Peculiar γ-ray binary LS I +61° 303

  the only one based on ''magnetar-like'' activity
  (although bursts very rare and weak)

A magnetar-like event from the X/γ-ray binary LS I +61° 303

NS (or BH ?) in eccentric orbit (26.5 days) around a Be star, D ~ 2 kpc
Periodic radio flares
GeV and TeV emission, weak X-ray emission,
No pulsations detected (→ also BH models are possible)



The Astrophysical Journal, 744:106 (18pp), 2012 January 10 — Torres et al.

Figure 1. *Swift*/BAT light curves of the burst detected in the direction of LS I +61°303.
(A color version of this figure is available in the online journal.)

Figure 2. *Swift*/BAT positional error circles overimposed to the *Chandra* image

Burst with 0.3 s duration and luminosity 2 10^{37} erg/s

In 2005: “Among the dozen magnetar candidates there are no binary objects” (Popov & Prokhorov, 2006)

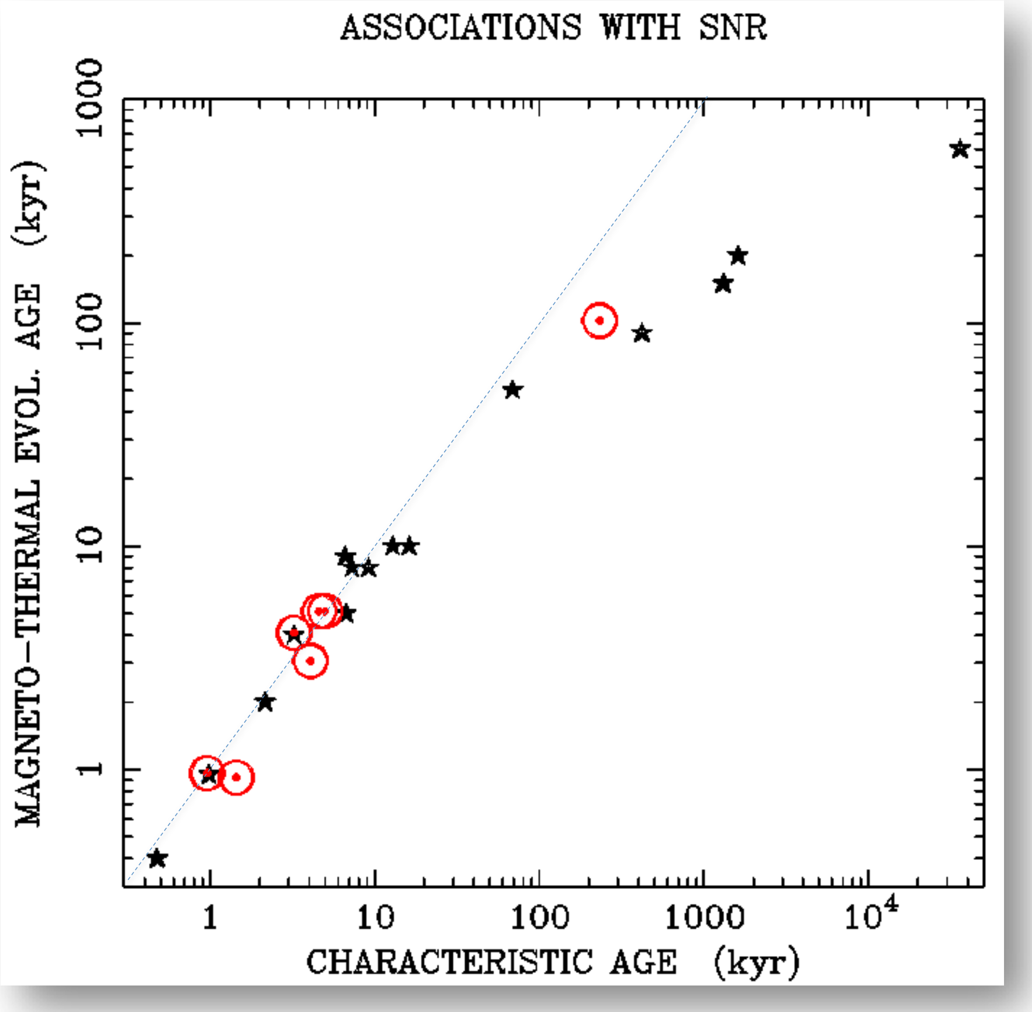
In 2015: several proposals, but no really convincing evidence for a binary magnetar

The sample has nearly doubled (23 magnetars)

Proper motions measured for 7 magnetars in NIR or radio band
→ V_T ~ 100-300 km/s → no evidence for large kicks

- Large kick velocities ✗
- Specific evolutionary paths ✓
- Observational selection effects ?

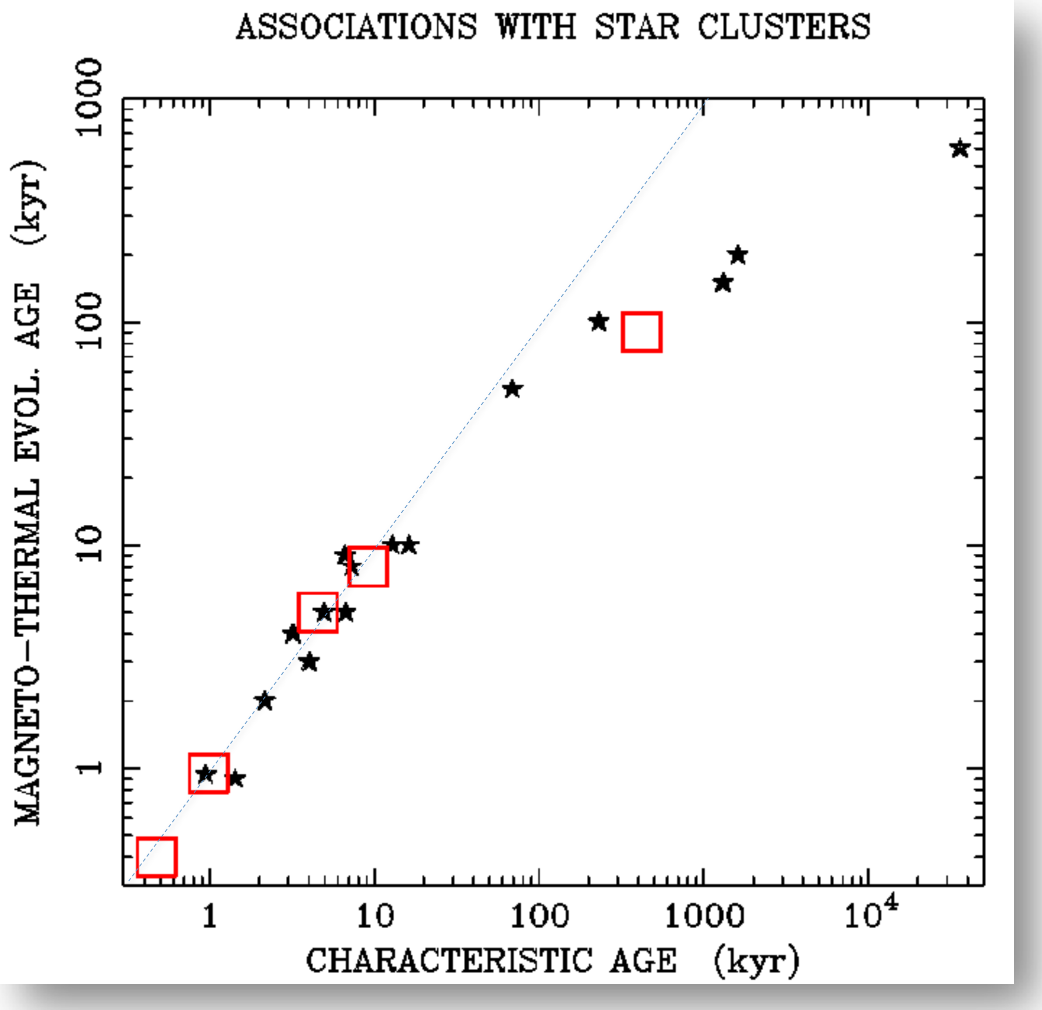
Associations with Supernova Remnants



The SNRs hosting magnetars do not differ from those associated to normal PSRs

→ No evidence for higher energy input, due e.g. to fast rotating NS
(Vink & Kuiper 2006, Martin+2014)

Associations with Clusters of Massive Stars



Lifetime of magnetars << lifetime of massive star clusters

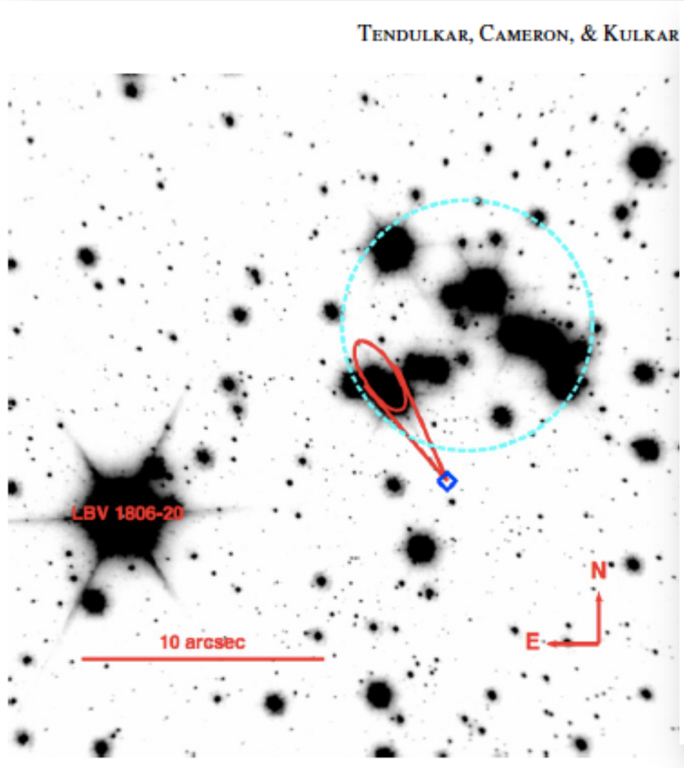
→ These associations provide constraints on the masses of the magnetar progenitors

AXPs/SGRs in massive star clusters

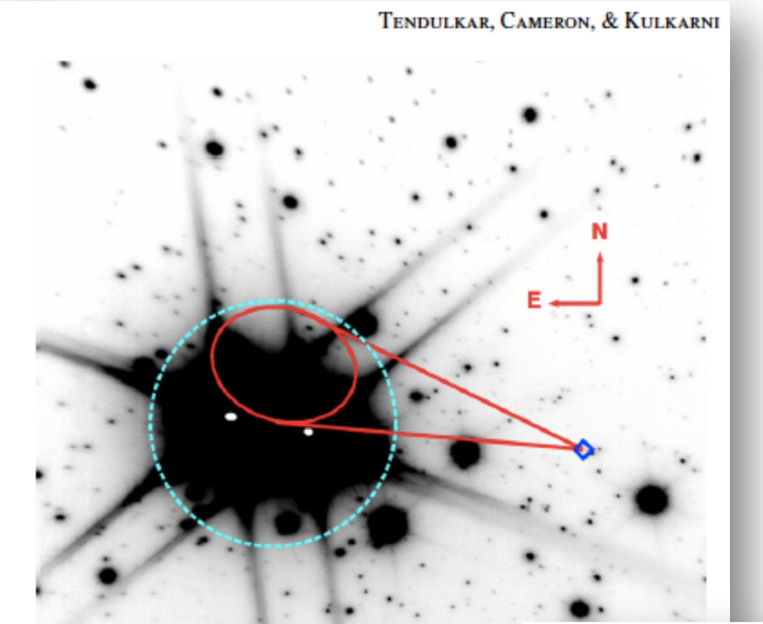
AXP/SGR	CLUSTER	AGE [Myr]	DISTANCE	PROGENITOR MASS [$M_\odot$]
SGR 1806-20	Cl 1806-20	4 +/- 1	8.7	40 ÷ 68
CXO J1647-45	Westerlund 1	~4.5	5	~ 55
SGR 1900+14	Cl 1900+14	10 - 16	12	13 ÷ 18
1E 1841-045	RSGC 2 / 3	16 +/- 4	6	~ 15
SGR 1745-29	Circum-nuclear cluster (disk)	~4	8.5	~ 50

Fuchs+ 99, Eikenberry+ 04, Muno+ 06, Bibby+ 08, Clark+ 08, 09, Bower+ 15

Proper motions and transverse velocities



SGR 1806-20
350+/- 100 km/s
for d=9 kpc



SGR 1900+14
130+/- 30 km/s
for d=12.5 kpc

Bower+ 2015

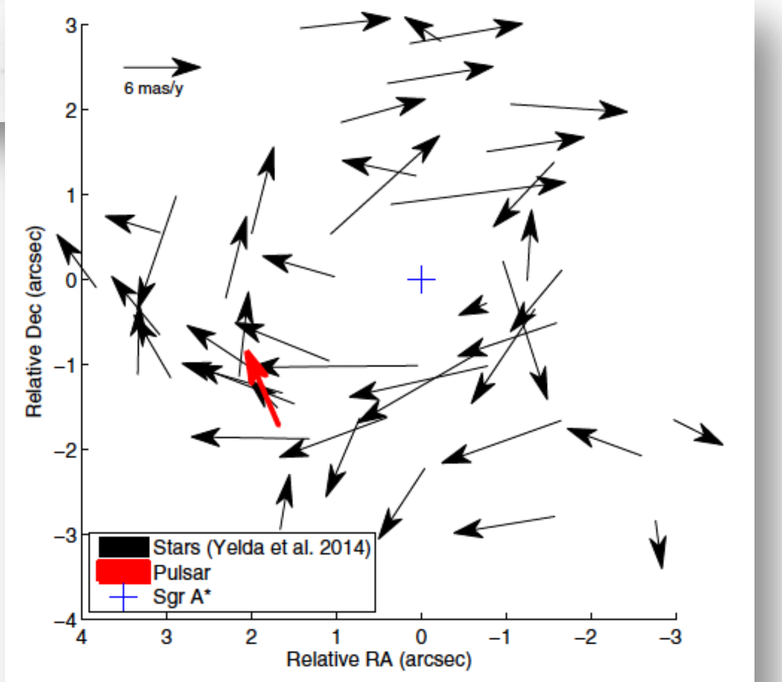
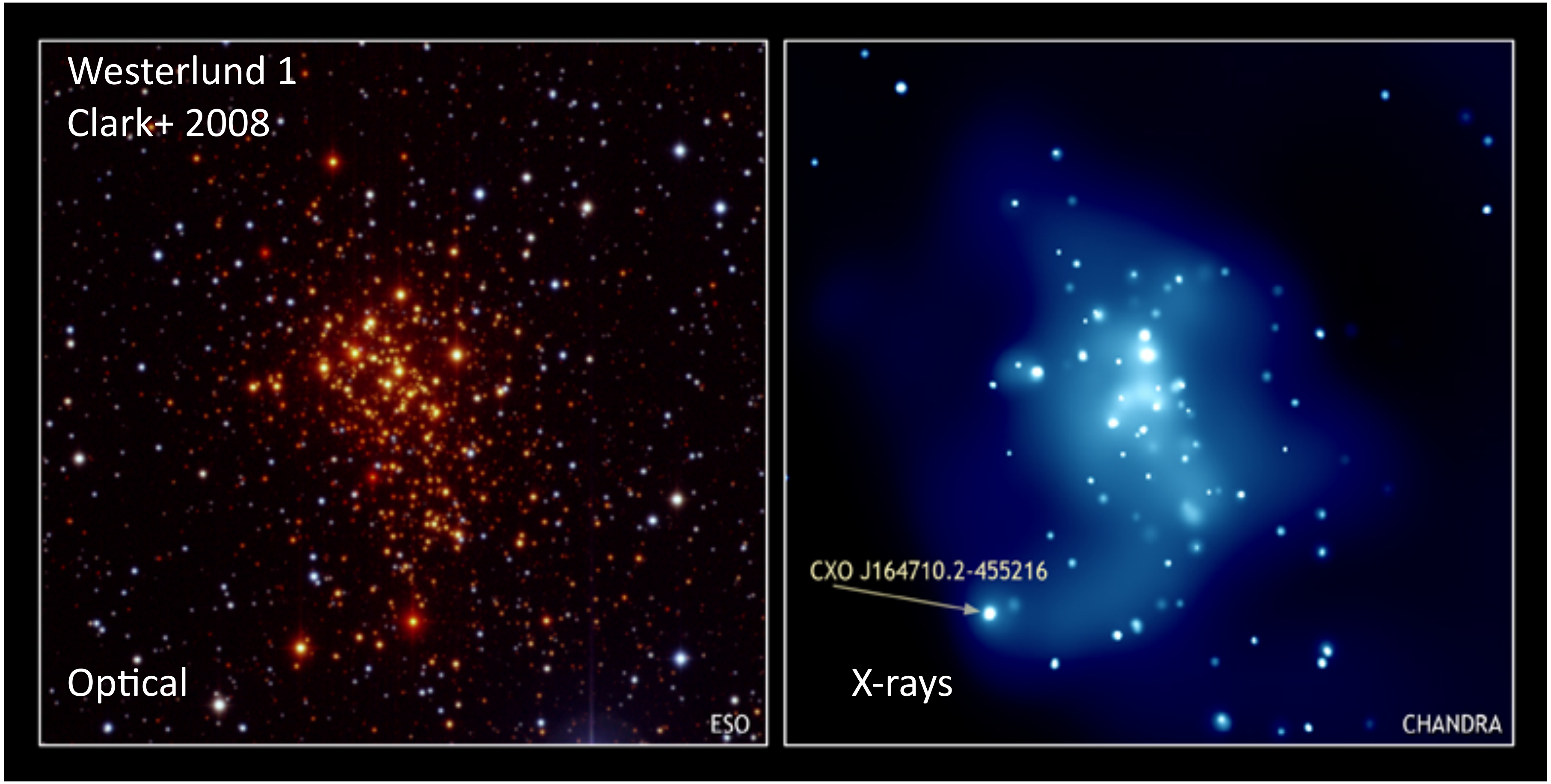


Figure 3. Proper motion of the pulsar along with stars from Yelda et al. (2014).

SGR 1745-29
236+/- 11 km/s
for d=8.3 kpc

A runaway star in Westerlund 1 identified as possible former companion of CXOU 1647 (Clark+ 2014)



Its high radial velocity consistent with kick in binary SNe

Its anomalous composition indicates binary evolution with mass transfer to a secondary which evolved first, forming the magnetar

Conclusions

Magnetars might be a large fraction of NS population (> 1% ÷ 10%)

but estimate subject to large uncertainties

- Small statistics
- Uncertain lifetime and recurrence times of outbursts
- Blurring of the different kinds of NS and evolutionary links

Bimodal distribution of progenitor masses >~ 40÷50 $M_\odot$ and ~15 $M_\odot$

→ Magnetars can be formed in different ways

Most massive stars are binary, but no strong evidence for binary magnetars

→ Either binaries do not form magnetars

→ Or those forming magnetars are more easily disrupted than those forming pulsars with lower B

→ Accretion reduces the magnetic field

Alternatively, the apparent lack of binary magnetars could be a selection effect.

Magnetar-like activity difficult to detect in the presence of accretion

Torques on NS driven by dipolar magnetic field → they do not give information on B inside the NS and in multipolar components