

Basic observational aspects of pulsar classes

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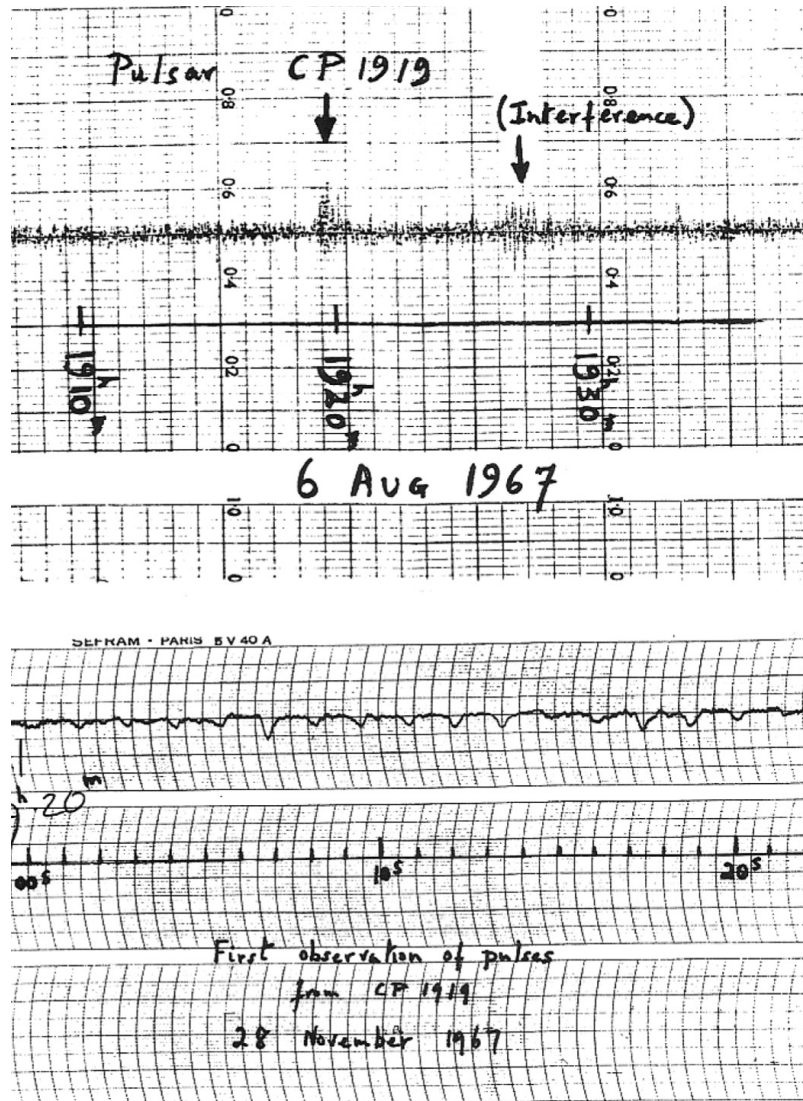
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The impact of a discovery



The pulsar CP1919 (for Cambridge Pulsar at **right ascension** 19h 19m) was barely distinguishable from interference on a scintillation survey chart (*top*).

On a higher-speed chart recording of CP1919 (*bottom*), dips in the upper trace spaced by $P \approx 1.3$ s, a series of periodic pulses.

Jocelyn Bell Burnell and Antony Hewish.

- **1931 Chandrasekhar** argued that WDs collapse at masses $> 1.4 M$
- **1934 Baade & Zwicky** proposed the existence of NS, they predicted their formation due to supernova explosion and their radius of ~ 10 km . (Baade & Zwicky 1934, Proc.Nat.Acad.Sci.)
- **1939 Oppenheimer & Volkoff** defined the first equation of state for a NS of mass ~ 1.4 Solar masses, a radius of ~ 10 km and a density of $\sim 10^{14}$ gr/cm³ (Oppenheimer & Volkoff, Phys.Rev)
- **1967 Pacini** predicted electromagnetic waves from rotating NSs and that such star might be powering the Crab nebula. (Pacini 1967 and 1968, Nature)

Order of magnitude

Why a short period implies a large density?

- Request: The centrifugal acceleration at the NS equator does not exceed the gravitational acceleration
 - If a nearly spherical star of mass M and radius R rotates with angular velocity $\Omega \equiv 2\pi/P$,

$$\Omega^2 R < \frac{GM}{R^2} \quad \Rightarrow \quad P^2 > \left(\frac{4\pi R^3}{3}\right) \frac{3\pi}{GM}$$

$$\rho \equiv M \left(\frac{4\pi R^3}{3}\right)^{-1} \quad P > \left(\frac{3\pi}{G\rho}\right)^{1/2} \quad \rho > \frac{3\pi}{GP^2}$$

- For instance, for a pulsar with ~ 1 s of period, the density should be larger than 10^8 g cm^{-3} . For Crab, at $P=0.033$ s, the density is > 1500 larger. For ms pulsars, it is of the order of $10^{14} \text{ g cm}^{-3}$, the density of an atomic nuclei.

Why a large density implies a small radius?

- Starting from the period inequality, maintaining the radius alive in the algebra,

$$P^2 > \left(\frac{4\pi R^3}{3}\right) \frac{3\pi}{GM} \quad \Rightarrow \quad R < \left(\frac{GMP^2}{4\pi^2}\right)^{1/3}$$

- A star whose mass is greater than the **Chandrasekhar mass** will collapse to form a neutron star (cannot be supported by the degeneracy pressure of electrons)

$$M_{\text{Ch}} \sim \left(\frac{\hbar c}{G}\right)^{3/2} \frac{1}{m_p^2} \approx 1.4M_{\odot}$$

- And so, a ms pulsar with a mass of 1.4 solar masses, will have a radius < 20 km

Why are pulsars so magnetic?

- Stars collapse from say 10^6 km to 10 km
- The size of a cross section of the stars ($\sim R^2$) collapses 10^{10} times
- **Magnetic flux conservation:** An initial magnetic field strength $B \sim 100$ G becomes $B \sim 10^{12}$ G
- This is actually a minimal estimation (dynamo effects, turbulence)

- **Conservation of angular momentum** during collapse also increases the rotation rate by about the same factor [$L \sim I/P$, with I moment of inertia, which is $\sim R^2$]
- This implies initial rotation periods P_0 in the millisecond range.
- Thus, young pulsars are fast, small, and magnetic; or rapidly rotating magnetic dipoles

What is the moment of inertia of a pulsar?

Moment of inertia is mass multiplied by square of the radial distance from its rotation axis.

For a sphere of radius R , mass M , and uniform density $\rho = 3M/(4\pi R^3)$ rotating around the z -axis

the moment of inertia is
$$I = \int_{-R}^R \left(\int_0^{(R^2 - z^2)^{1/2}} \rho r^2 2\pi r \, dr \right) dz,$$

with z being the height in cylindrical coordinates, and r is the distance from the rotation axis (i.e., integral over the slices of the sphere). Then:

$$I = \pi \rho \int_0^R (R^2 - z^2)^2 dz = \frac{8\pi \rho R^5}{15} = \frac{2MR^2}{5}$$

$$I = \frac{2MR^2}{5} \approx \frac{2 \cdot 1.4 \cdot 2.0 \times 10^{33} \text{ g} \cdot (10^6 \text{ cm})^2}{5} \approx 10^{45} \text{ gm cm}^2.$$

- Pulsars slow down: losing rotational energy

$$E = \frac{1}{2} I \omega^2 = \frac{I}{2} \left(\frac{4\pi^2}{P^2} \right) = \frac{2I\pi^2}{P^2}$$

- Then, the rate of energy release (the spin-down power)

$$\frac{dE}{dt} = \frac{d}{dt} \left(\frac{2I\pi^2}{P^2} \right) = -\frac{4I\pi^2}{P^3} \frac{dP}{dt}$$

- This is the energy reservoir for everything that happens in the surrounding of the pulsar unless there is an additional source of energy, beyond the rotation itself
- This power is what is used to emit at all frequencies, and to power the ‘wind nebula’.

Is the pulsar power large?

- It can be. For Crab, for instance:

$$-\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3} = \frac{4\pi^2 \cdot 10^{45} \text{ g cm}^2 \cdot 10^{-12.4} \text{ s s}^{-1}}{(0.033 \text{ s})^3} \approx 4 \times 10^{38} \text{ erg s}^{-1} \approx 10^5 L_{\odot}$$

- If a pulsar spins down from an initial spin period P_0 such that

$$d\Omega/dt = -k\Omega^n \text{ (where } \Omega = 2\pi/P \text{ and } n \text{ is the “braking index”),}$$

then the spin-down power can also be written as

$$L(t) = L_0 (1 + t/\tau_0)^{-(n+1)/(n-1)}$$

Where τ_0 is the initial spin-down timescale and L_0 is the initial luminosity.

This indicates that most of the power is injected for $t < \tau_0$

Magnetic dipole radiation and minimum magnetic field

Equating the magnetic dipole radiation with the spin-down power and solving for B

$$\begin{aligned}P_{\text{rad}} &= -\dot{E}, \\ \frac{2}{3c^3} (BR^3 \sin \alpha)^2 \left(\frac{4\pi^2}{P^2} \right)^2 &= \frac{4\pi^2 I \dot{P}}{P^3}, \\ B^2 &= \frac{3c^3 I P \dot{P}}{2 \cdot 4\pi^2 R^6 \sin^2 \alpha}, \\ B &> \left(\frac{3c^3 I}{8\pi^2 R^6} \right)^{1/2} (P \dot{P})^{1/2} \approx 3.2 \times 10^{19} \left(\frac{P \dot{P}}{\text{s}} \right)^{1/2}\end{aligned}$$

For the Crab pulsar, for instance, this is $\sim 10^{12}$ G

Is the magnetic field large?

-The field of a refrigerator magnet is about 1 G

-The energy density of the magnetic field is

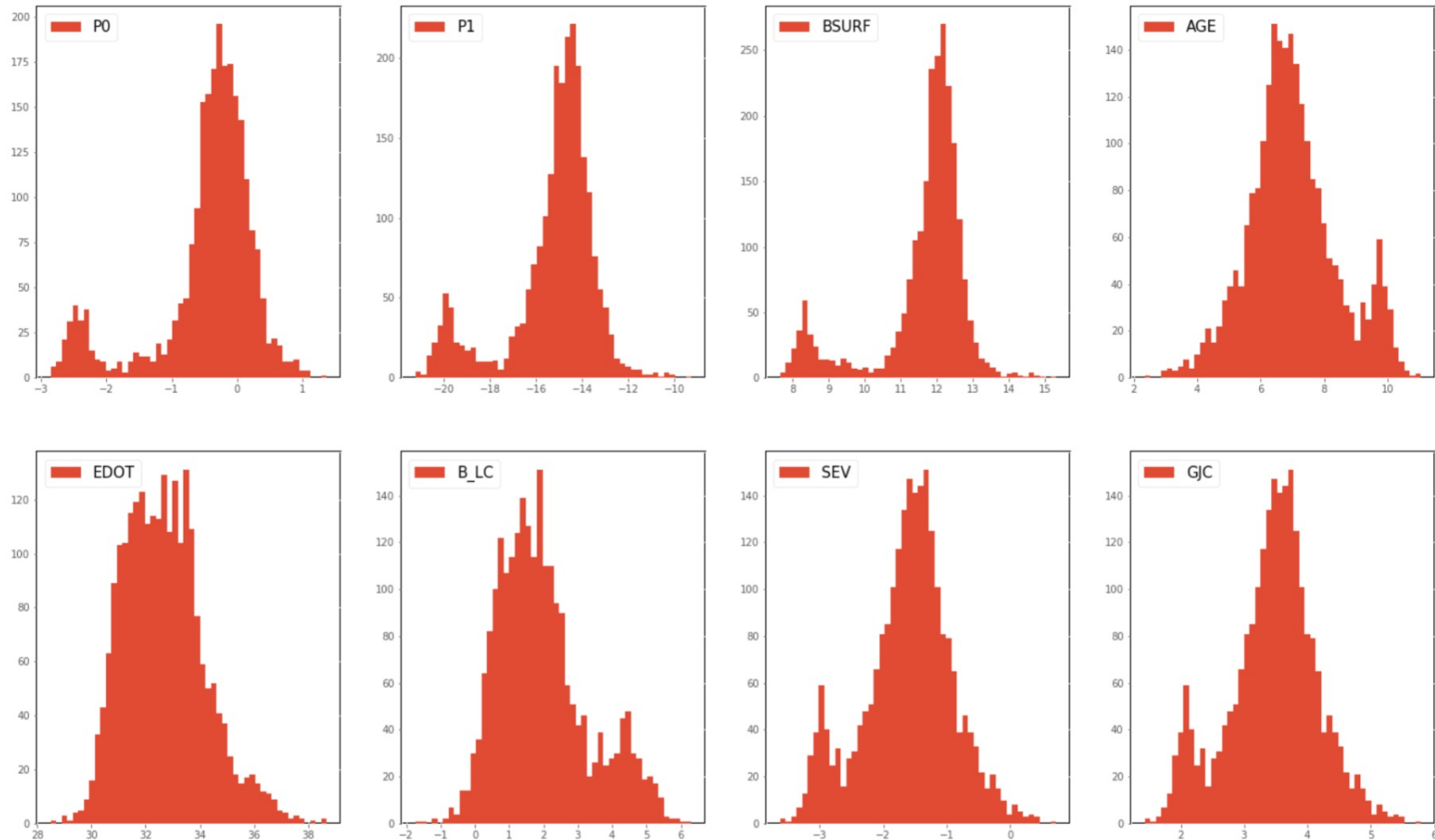
$$U_B = \frac{B^2}{8\pi} > 6 \times 10^{23} \text{ erg cm}^{-3}$$

so 1 cm³ of this is about 6 x 10¹⁶ Joules or 6 x 10¹⁶ W / s

Everyday comparison: 1 J is the energy required to lift a medium-size apple (100 g) 1 meter vertically from the surface of the Earth.

Pulsar's spin-down basics III: Using P and its derivative


from Rodriguez, DFT, Patruno, 2021 in preparation



Distribution of the logarithm of all quantities


The pulsar zoo seen in observations

The ATNF pulsar catalog

 Accessibility menu

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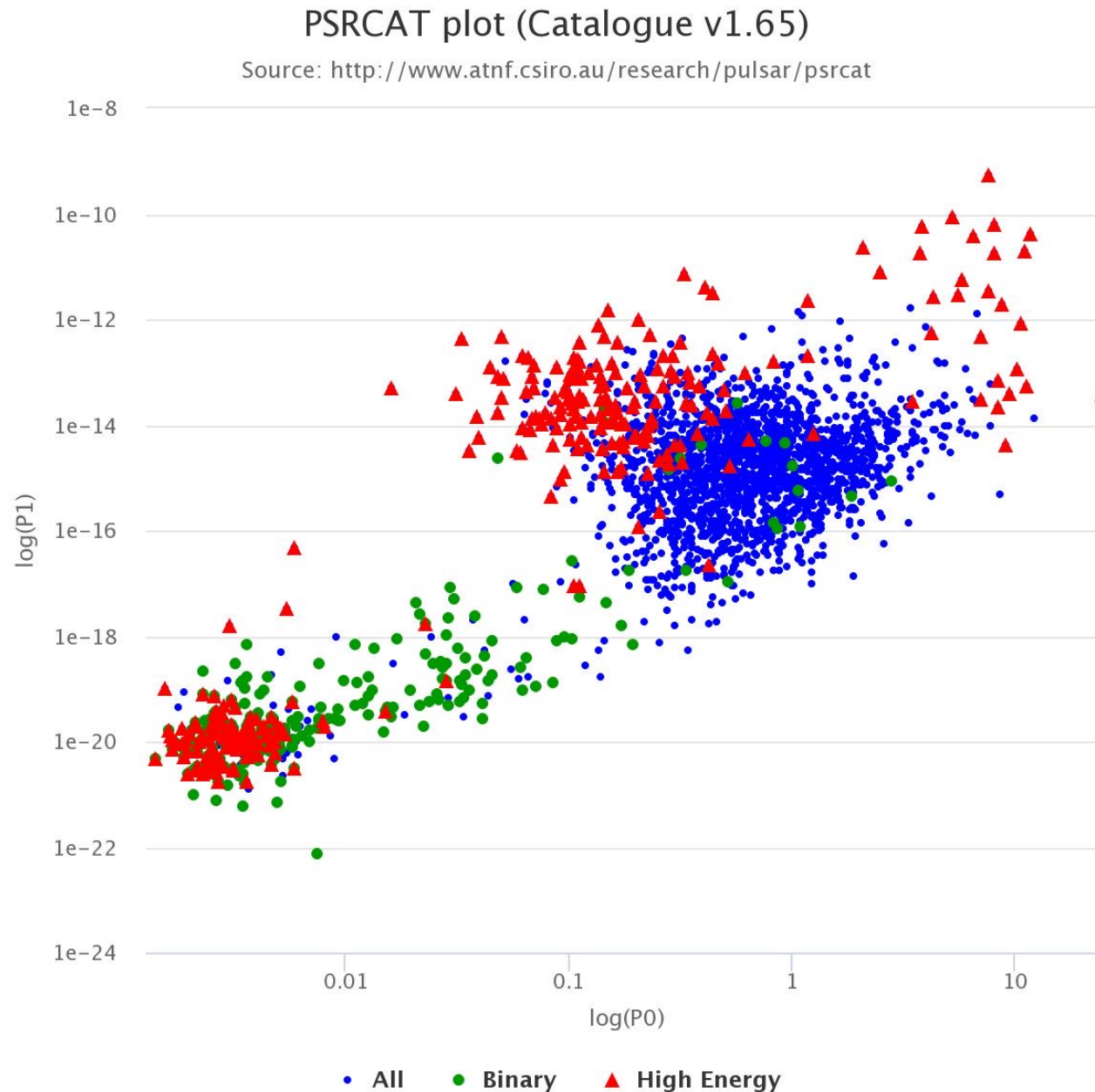
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Catalogue version: 1.65

Predefined Variables [Display parameters](#)

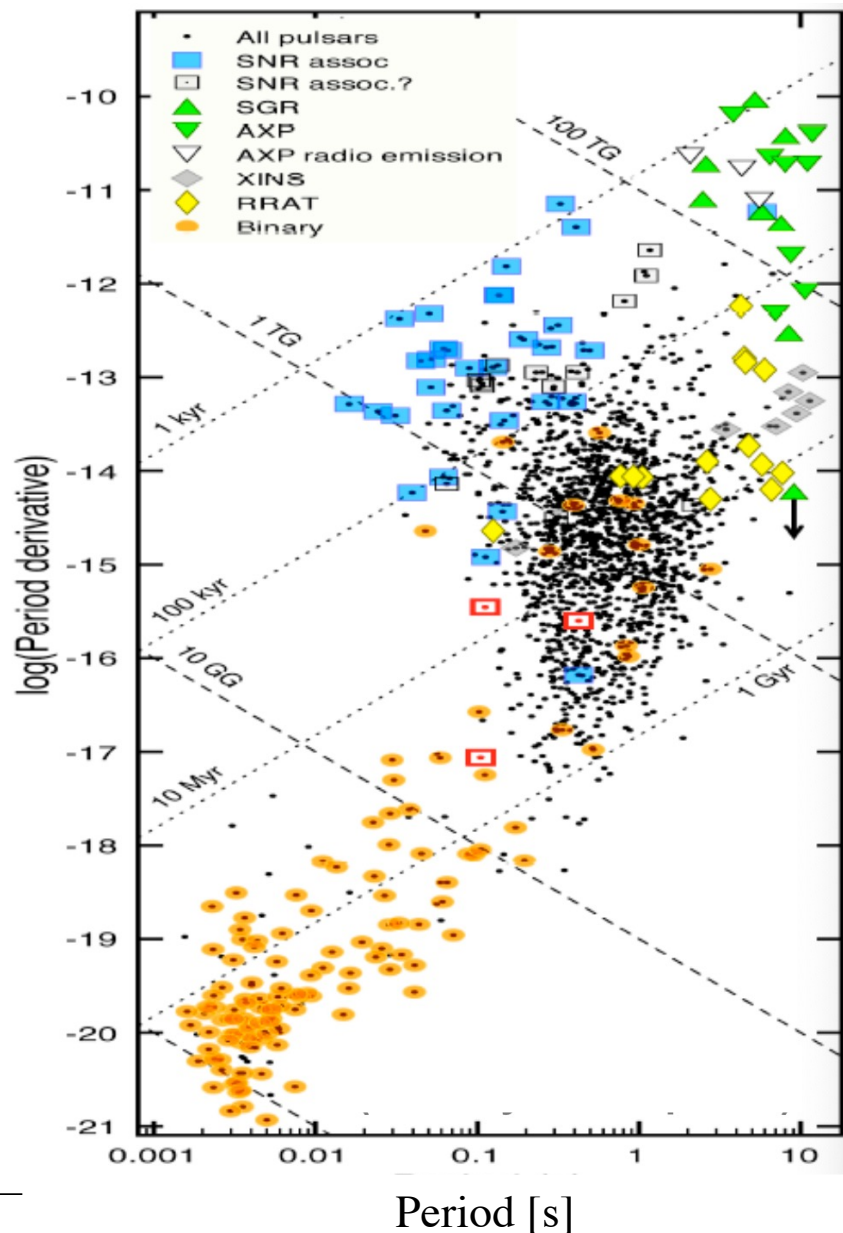
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<input type="checkbox"/> PX	<input type="checkbox"/> PosEpoch	<input type="checkbox"/> ELong	<input type="checkbox"/> ELat	<input type="checkbox"/> PMELong	<input type="checkbox"/> PMELat
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				<input type="checkbox"/> S350	<input type="checkbox"/> S600
					<input type="checkbox"/> S700

The ATNF pulsar catalog: direct plot of P and Pdot



Highcharts.com

The PPdot diagram



-Magnetars: B-powered

-XDINS: kT-powered

-Pulsars with SNRs associations

-Pulsars and RRATs: rotation-powered

-CCOs: kT-powered

-Recycled binaries: rotation-powered / accretion powered pulsars / transitional pulsars

Magnetars

How are magnetars discovered?

Short X/gamma-ray bursts
(confused with GRBs)

Bright X-ray pulsars with 0.5-10 KeV
Spectra modelled by thermal plus non-thermal component

Bright X-ray transients

(different name/similar nature)

We believe there is no physical distinction between Anomalous X-ray Pulsars, Soft Gamma Repeaters, and Transient Magnetars: all showing all kind of magnetar-like activity.

Magnetar flares

Short bursts

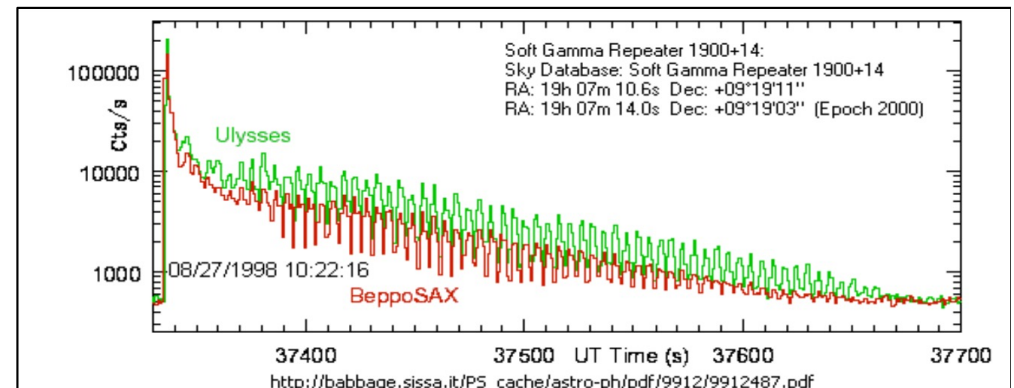
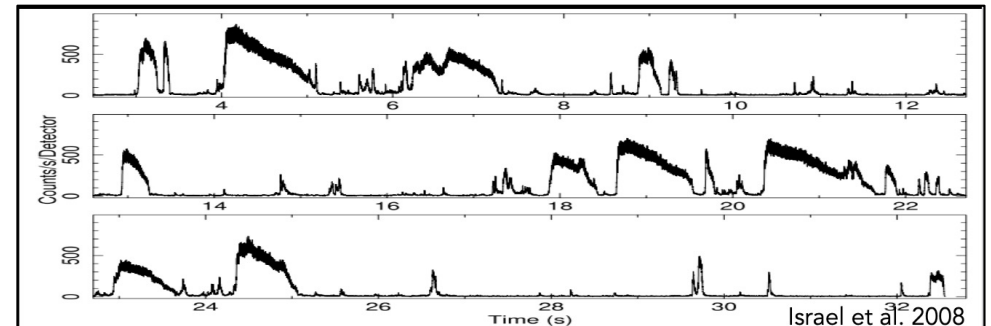
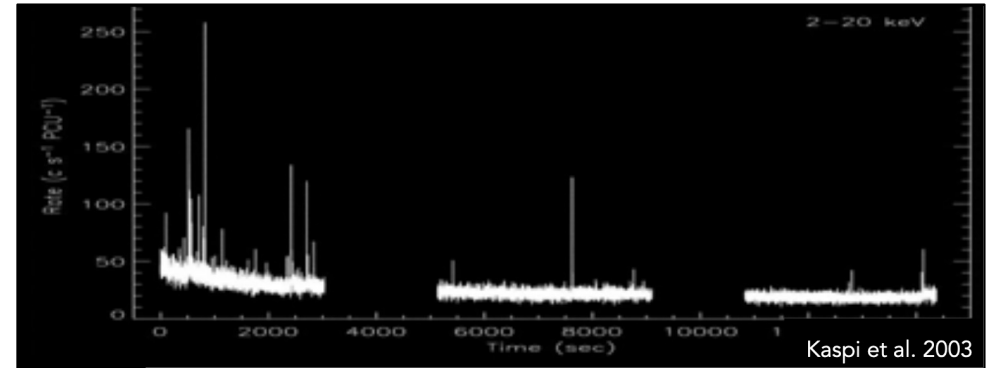
- the most common
- they last ~ 0.1 s
- peak $\sim 10^{41}$ ergs/s
- soft γ -rays thermal spectra

Intermediate bursts

- they last 1-40 s
- peak $\sim 10^{41}$ - 10^{43} ergs/s
- abrupt on-set
- usually soft γ -rays thermal spectra

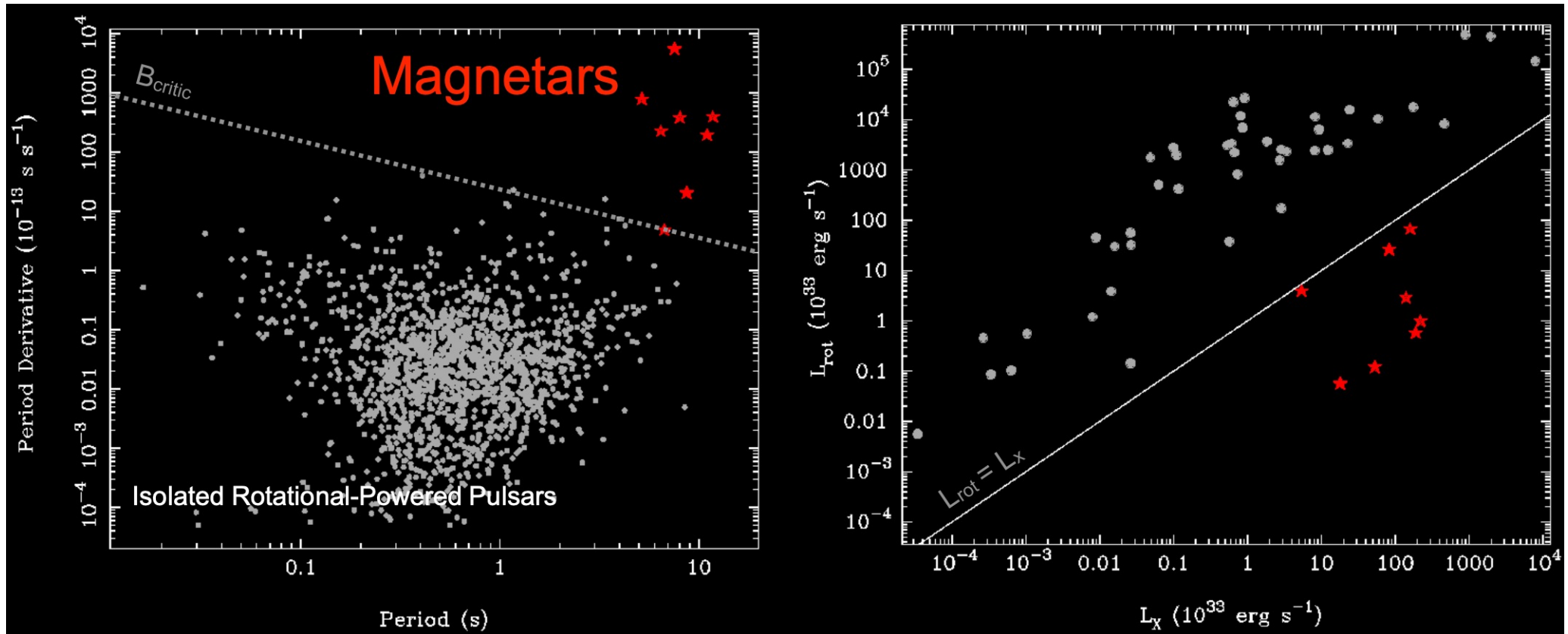
Giant Flares

- their high-energy output is exceeded only by blazars and GRBs
- peak energy $> 3 \times 10^{44}$ ergs/s
- < 1 s initial peak with a hard spectrum which rapidly become softer in the burst tail that can last > 500 s, showing the NS spin pulsations, and quasi periodic oscillations (QPOs)



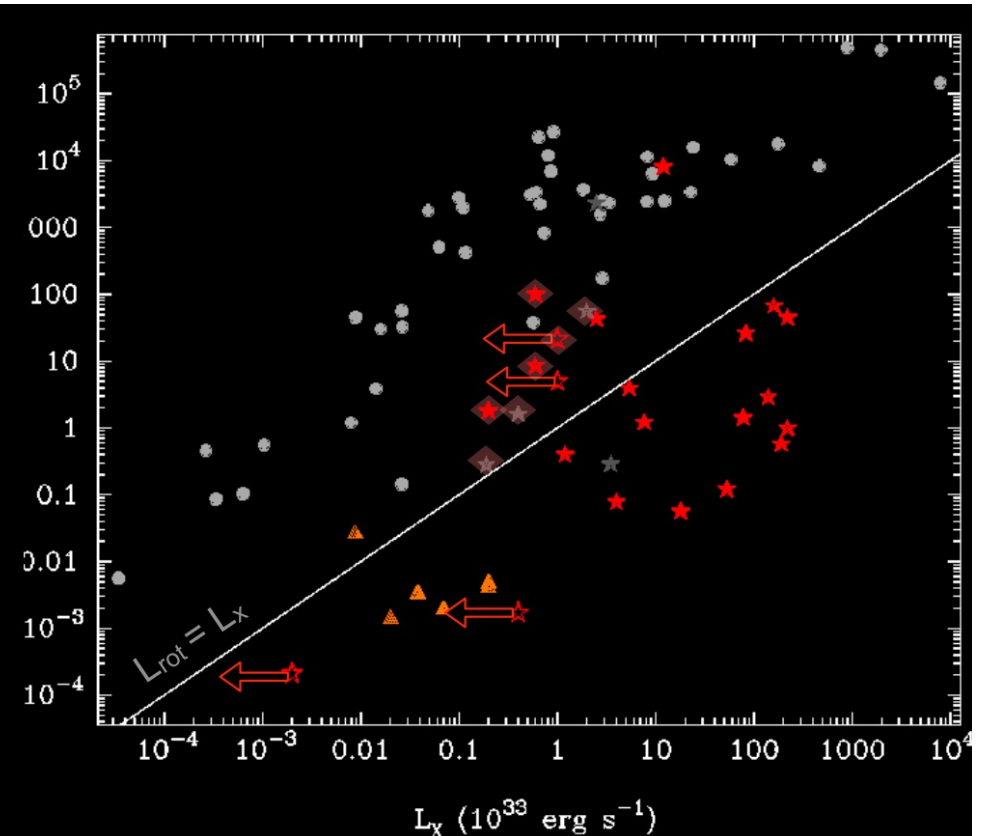
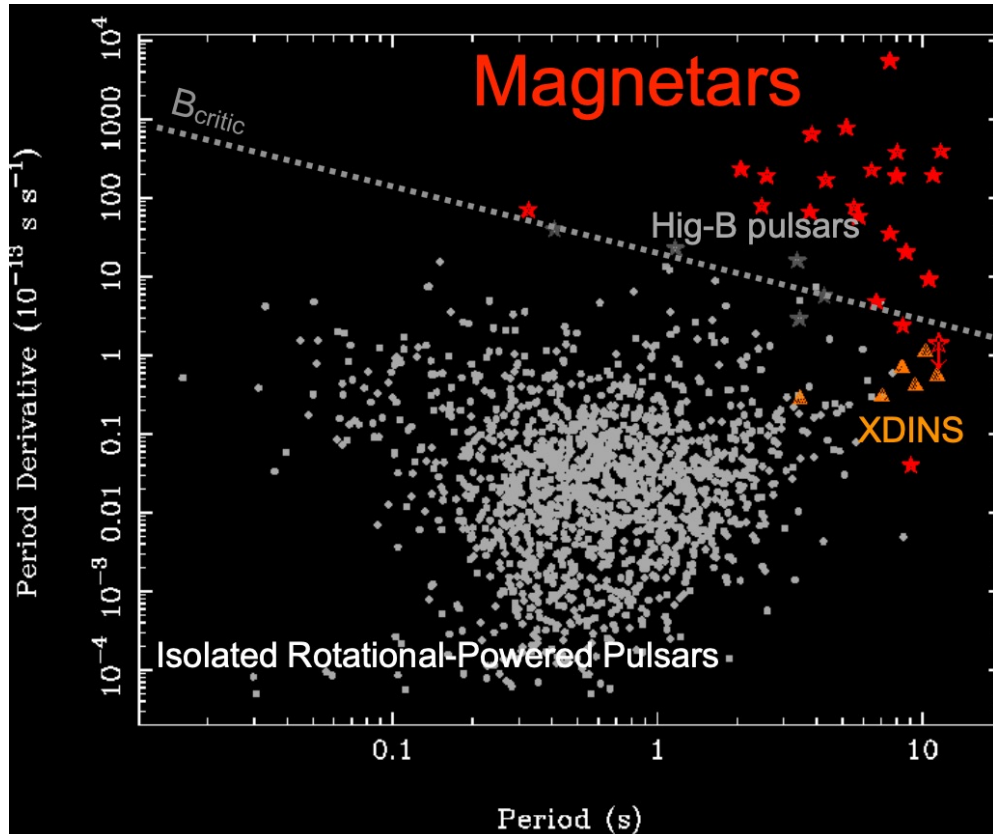
Are magnetars any different from the rest? ... they used to be

- Magnetic fields $> B_{\text{critical}} \sim 4.4 \times 10^{13}$ Gauss
- X-ray luminosities exceed rotational power
- Stable soft X-ray pulsars with $P \sim 5\text{-}10\text{ s}$ and $L_x \sim 10^{34\text{-}35}$ erg/s
- Radio quiet X-ray pulsars
- No pulsar wind nebulae



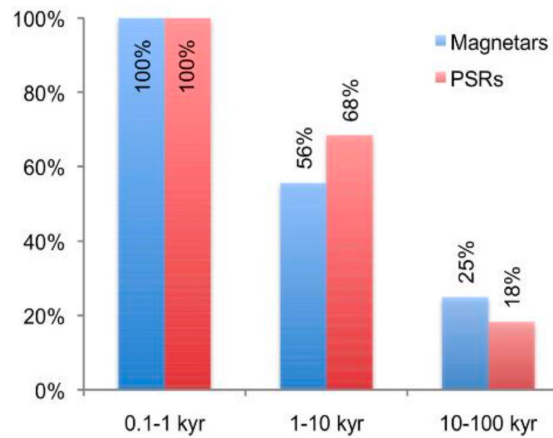
Not any longer

- Magnetic fields NOT always $> B$ critical
- X-ray luminosities does not always exceed rotational power
- They are not stable soft and hard X-ray pulsars
- They emit in radio at least during transient events
- They can host a pulsar wind nebulae, even if rotationally-powered

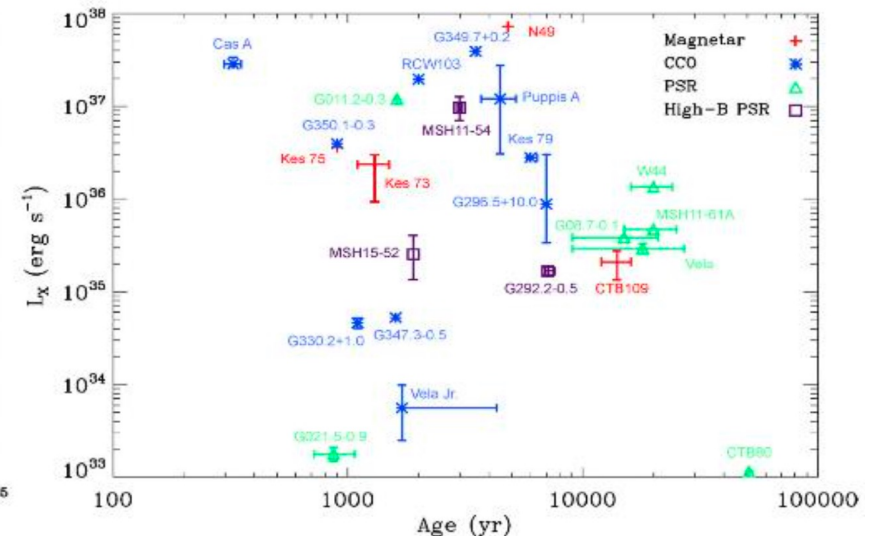
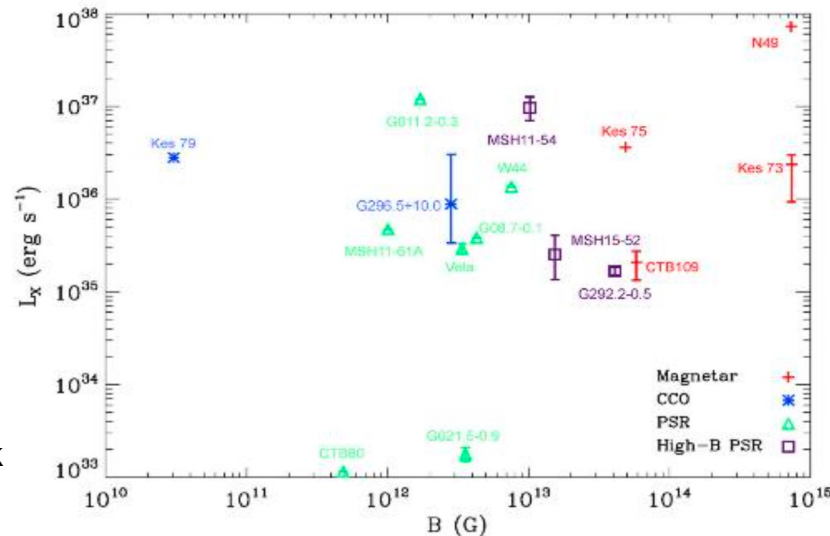
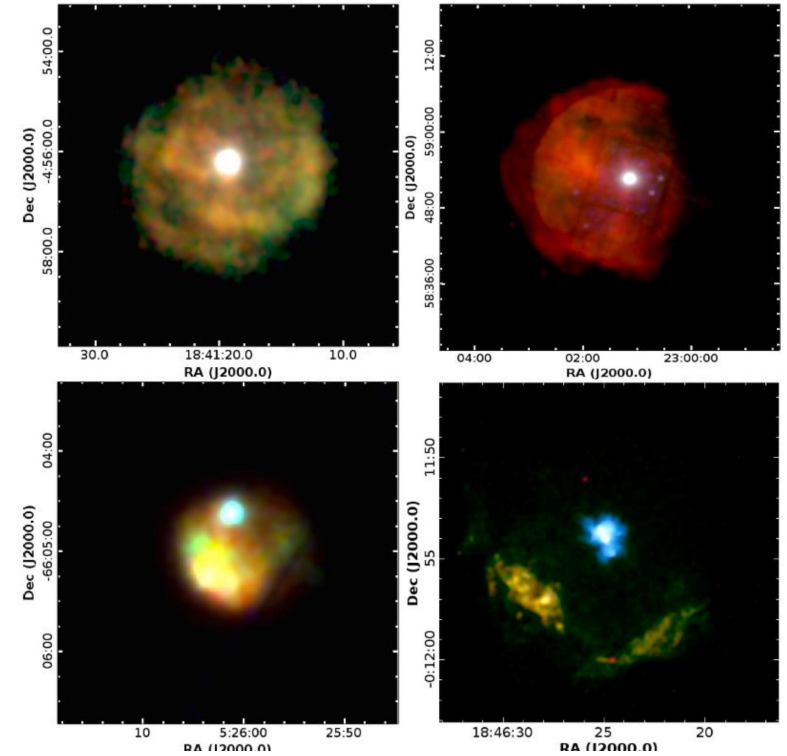


Their SNRs are also similar to the rest

Magnetar SNRs are similar in energetics, ionization states and detectability, to normal pulsar SNRs.

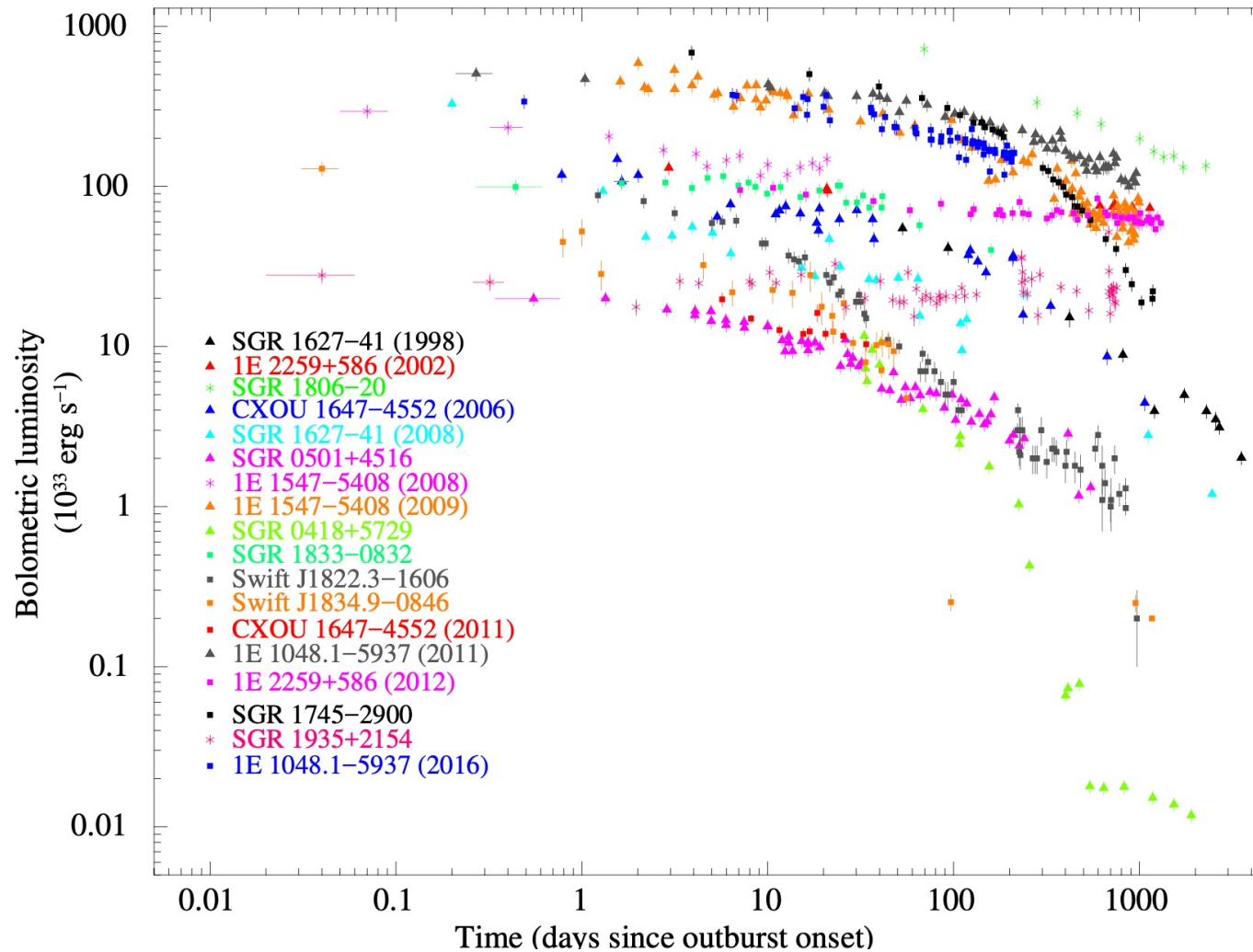


Kes73 → 1E 1841-045
 CTB109 → 1E 2259+586
 N49 → SGR 0526-66 (LMC)
 Kes75 → PSR 1846-0258



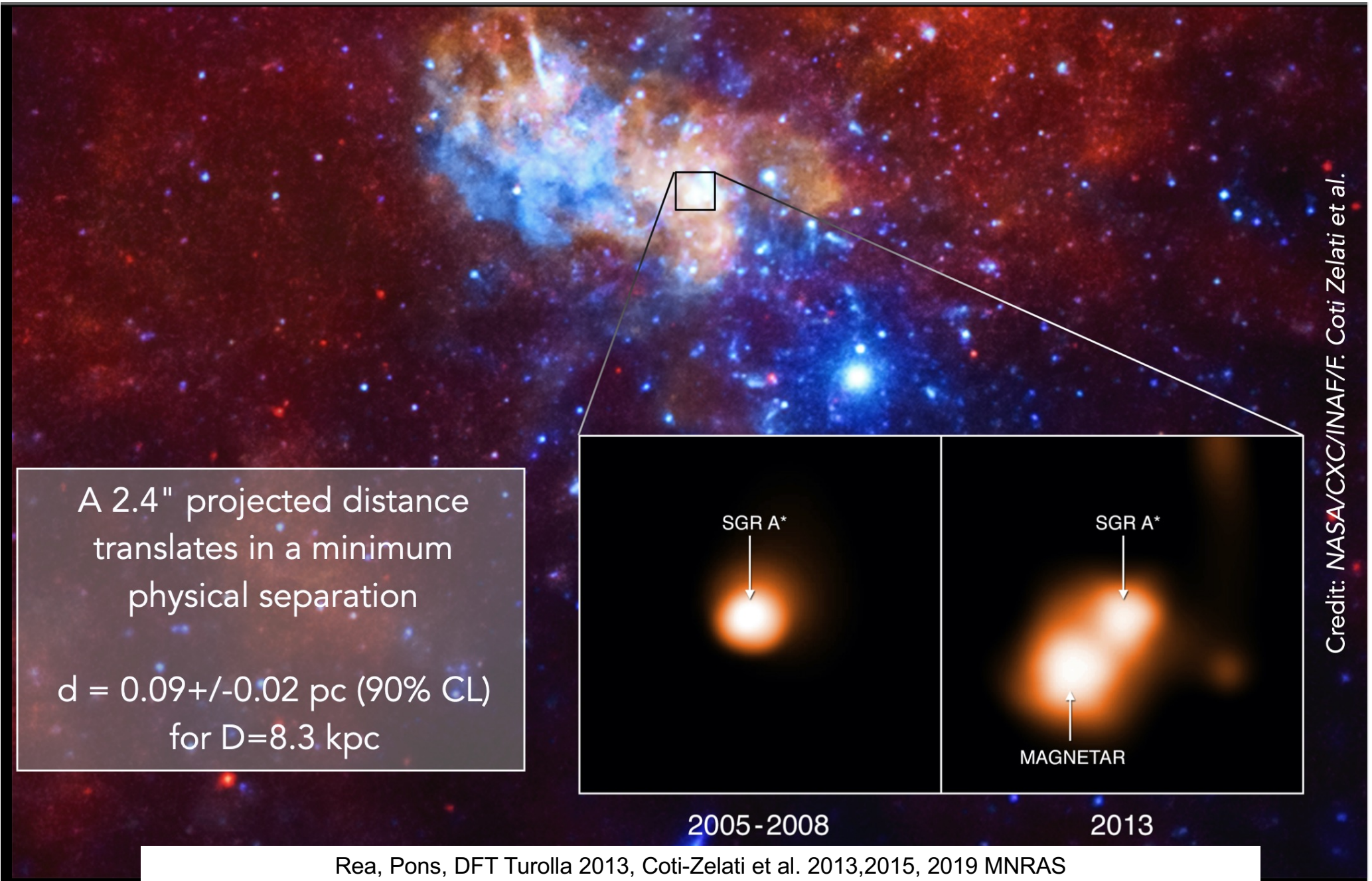
Martin, Rea, DFT
 & Papitto 2014,
 MNRAS; also Vink
 & Kuiper 2006

Variety of timescales for the decay of emission (months, years)



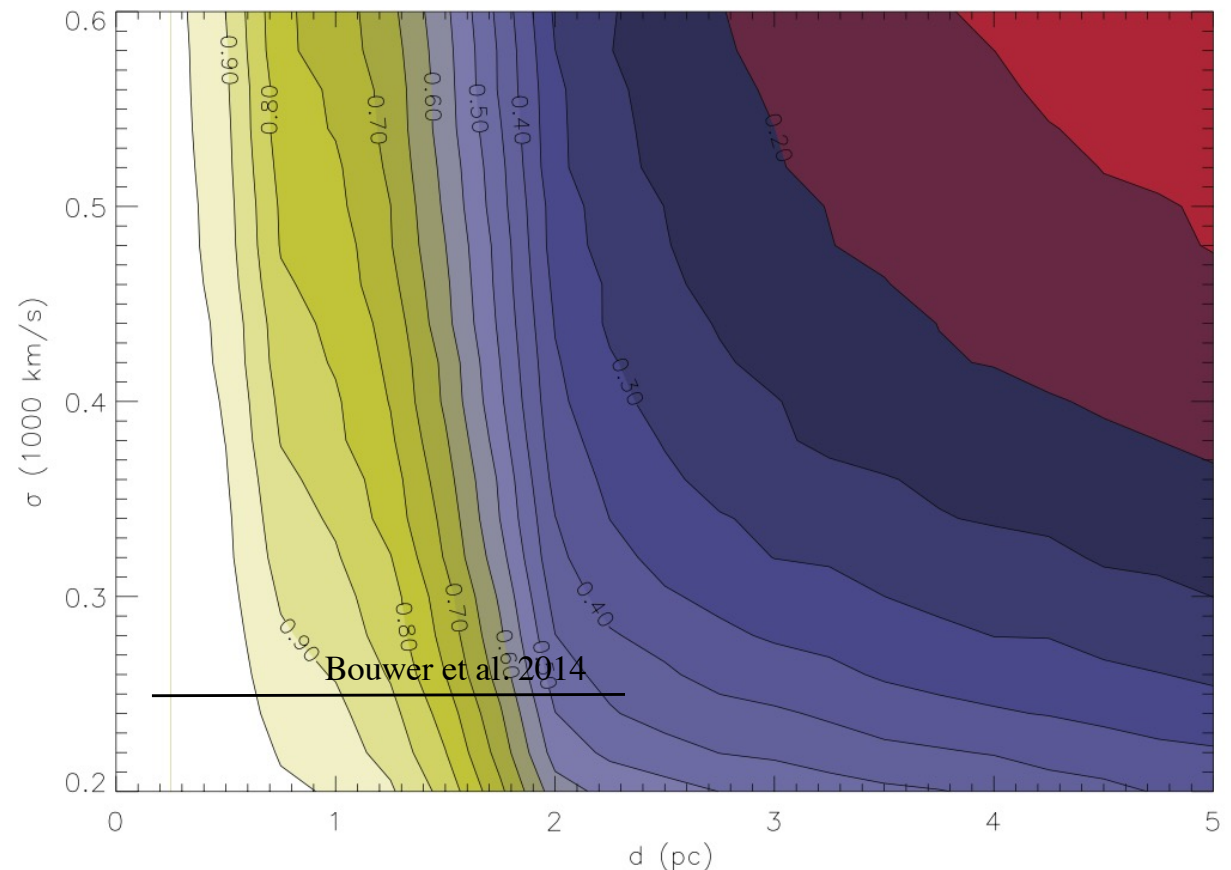
Coti-Zelati et al. 2018

Magnetar in the Galactic center



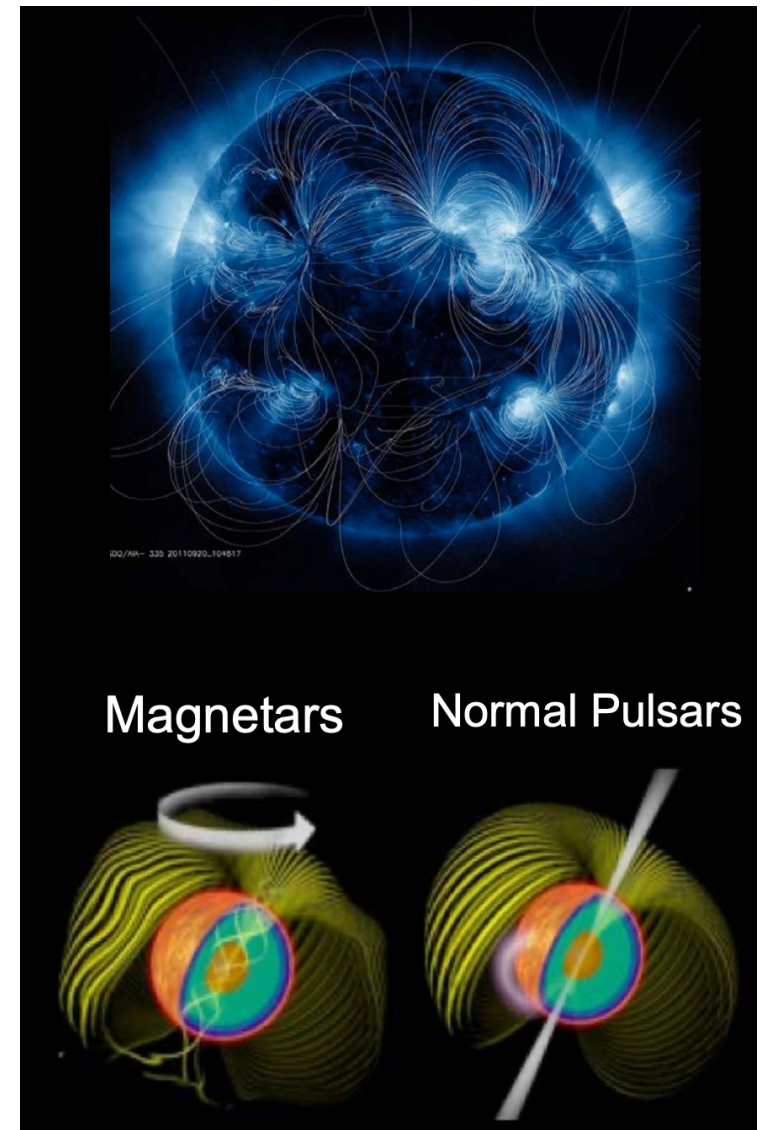
The probability of SGR J1745–2900 being in a bound orbit around Sgr A* depends on the distance and the kick velocity of the neutron star at birth.

- $P \sim 3.76$ s
- $\dot{P} \sim 0.4 - 6.6 \times 10^{-12}$ s/s
- $B_{\text{dip}} \sim 2 \times 10^{14}$ G
- $L_{\text{sd}} \sim 5 \times 10^{33}$ erg/s
- $\tau_c \sim 9$ kyr
- Radio pulsed emission at $DM = 1750 \pm 50$ pc cm $^{-3}$ (the highest ever detected for a radio pulsar)
- Thermal spectrum: 0.95 keV cooled down to 0.85 keV plus faint non-thermal component
- tiny (~ 1 km) hot spot which temperature cools down very slowly
- Column density $N_h = 0.98(4) \times 10^{23}$ cm $^{-2}$
- Slow flux decay, a factor of 2-3 in one yr.



What powers a magnetar?

- Twisting / untwisting of the magnetic field
- Magnetars are assumed to have complex magnetic field morphologies, both inside and outside the star.
- The surface of young magnetars are so hot that they are bright in X-rays.
- Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.
- Twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing the outburst onset and evolution.



Magnetar phenomenology can come from fields within the star, in an otherwise normally looking pulsar.

Pulsars in binaries

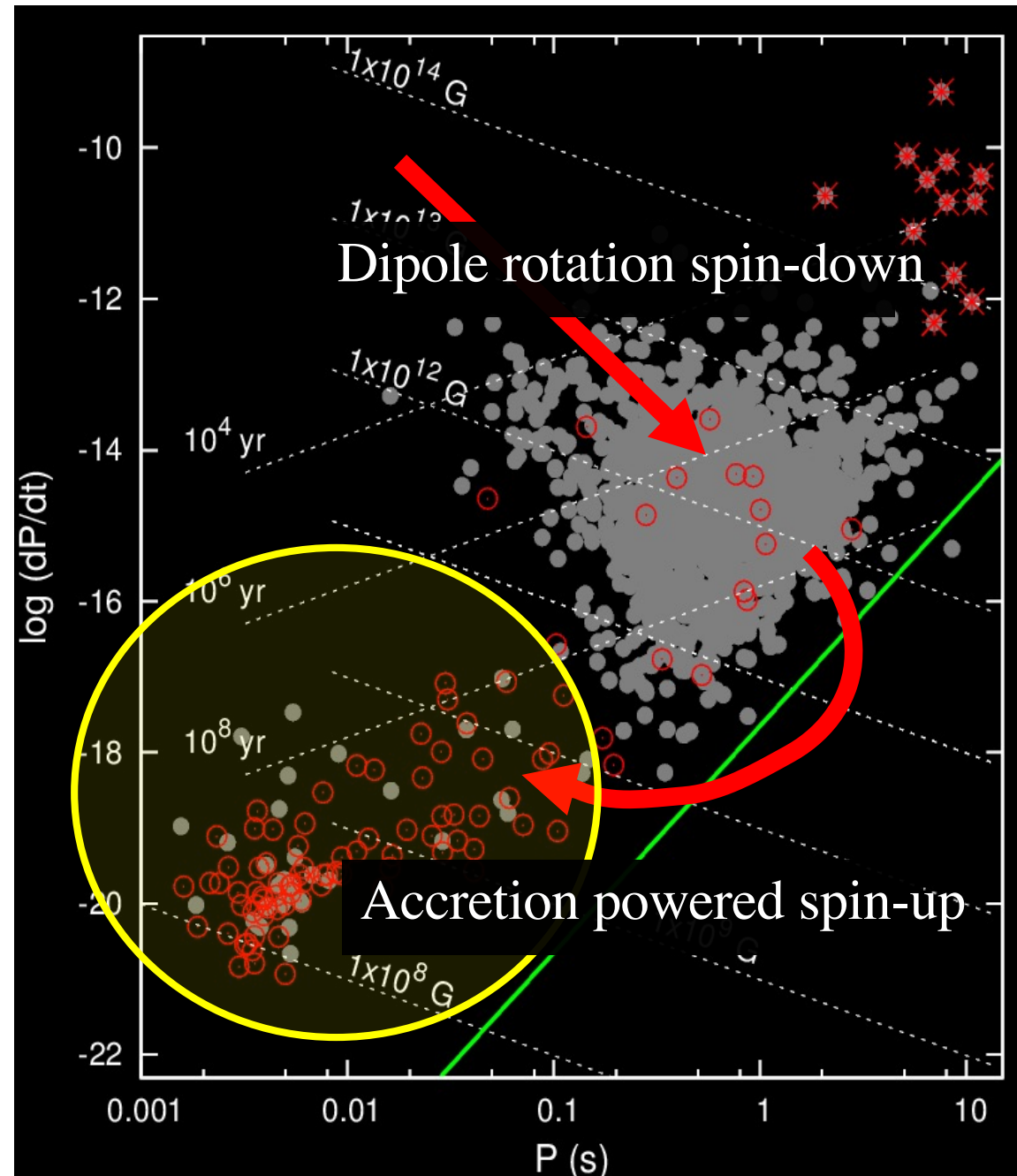
Millisecond pulsars

[Backer+ 1982 Nature]

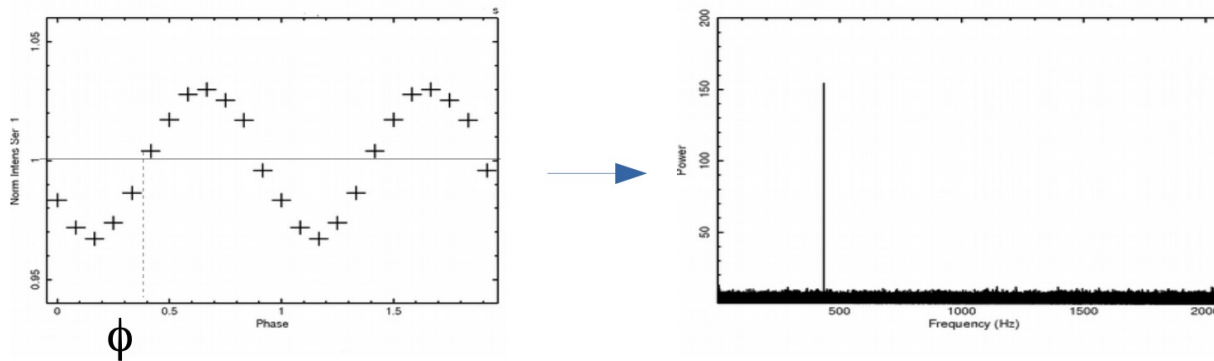
- weakly magnetized
- often found in globular clusters
→ old systems
- often in binaries

Neutron star recycling

Bisnovatyi-Kogan & Komberg 1974
Alpar+, Radhakrishnan+ 1982



Millisecond pulsars as clocks, timing technique



Fourier techniques to detect a coherent periodicity

$$\delta \nu = \frac{1}{\Delta t_{obs}} \quad \delta P = \frac{P^2}{\Delta t_{obs}} \quad \sim 0.3 \text{ ns } (2 \times 10^{-10} \text{ s}) \text{ accuracy reached over } \Delta t_{obs} \sim \text{hour}$$

A better precision is achieved through phase fitting

$$\delta \nu = \frac{\delta \phi}{\Delta t_{obs}} \quad \delta P = \frac{P^2 \delta \phi}{\Delta t_{obs}} \quad \sim 10 \text{ ps } (10^{-11} \text{ s}) \text{ accuracy reached over } \Delta t_{obs} \sim \text{hour}$$

If the frequency evolution is 'stable', observations spanning large intervals can be tied together

$$\delta \nu = \frac{\delta \phi}{\Delta t_{span}} \quad \delta P = \frac{P^2 \delta \phi}{\Delta t_{span}} \quad \sim 1 \text{ fs } (10^{-15} \text{ s}) \text{ accuracy reached over } \Delta t_{span} \sim \text{year}$$

Millisecond pulsars as clocks, a lot to take into account

A MSP in a binary system is a clock falling in the gravitational field of the companion

Keplerian parameters

- orbital period
- projected size of pulsar orbit
- orbital phase
- eccentricity
- longitude of periastron

Post-Keplerian parameters

- rate of periastron advance
- orbital period decay
- Einstein delay
- Shapiro delay & shape

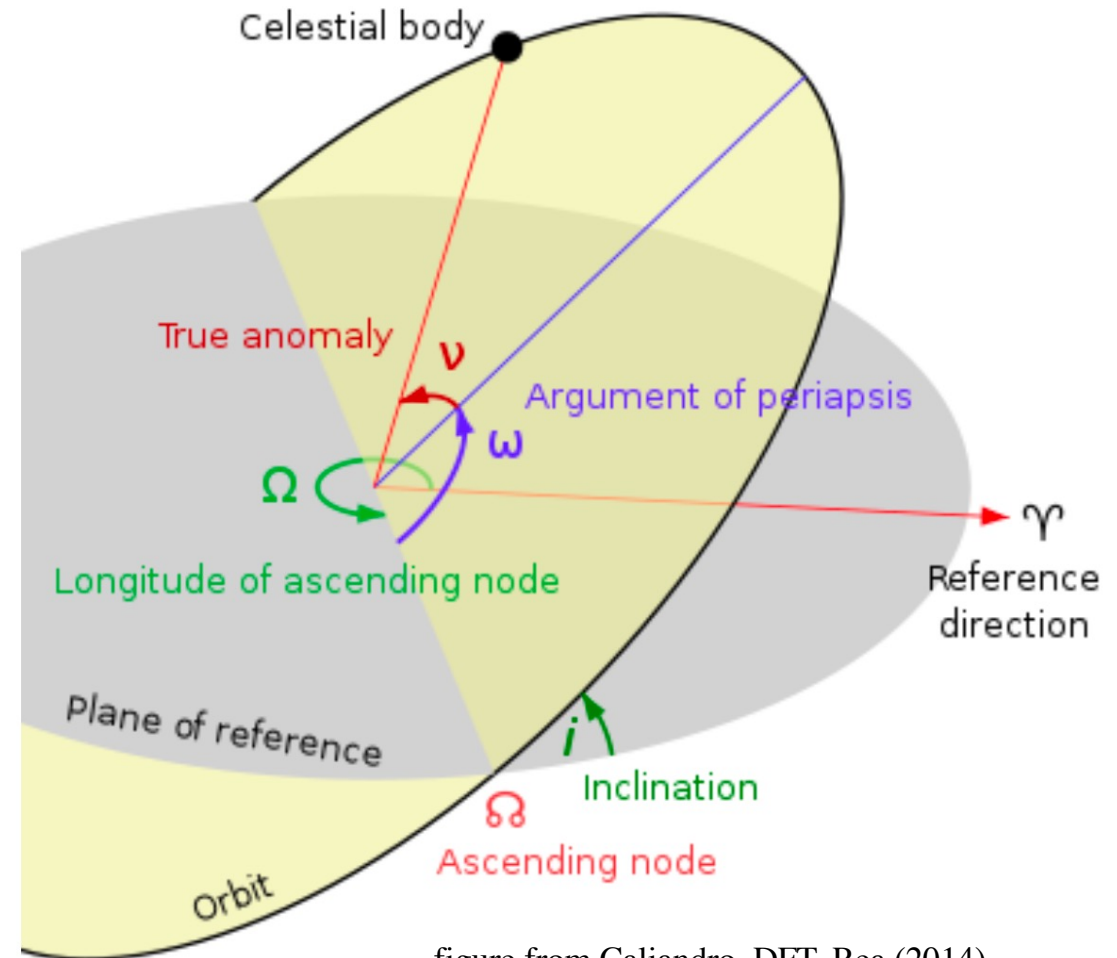


figure from Caliendo, DFT, Rea (2014)

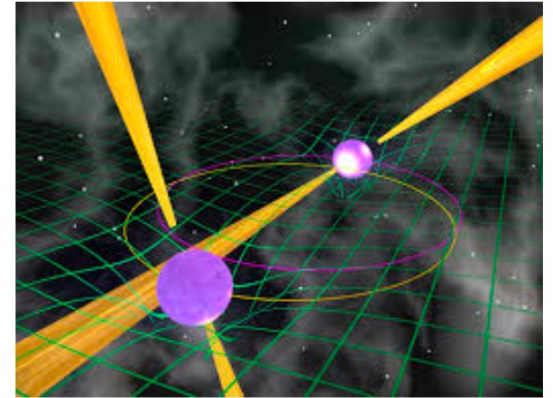
Position and motion

Millisecond pulsars as clocks, a lot to take into account

Test General Relativity in the weak field regime (but stronger than in Solar System)

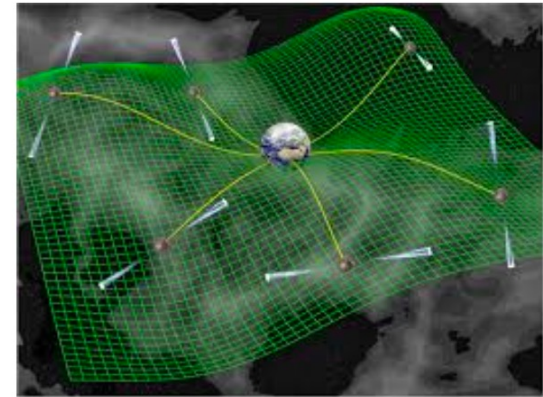
Test strong equivalence principle (grav mass = inertial mass)

- pulsar + white dwarf binaries in the Galaxy grav. Field
- pulsar in a triple system (e.g. Ransom et al. 2014)

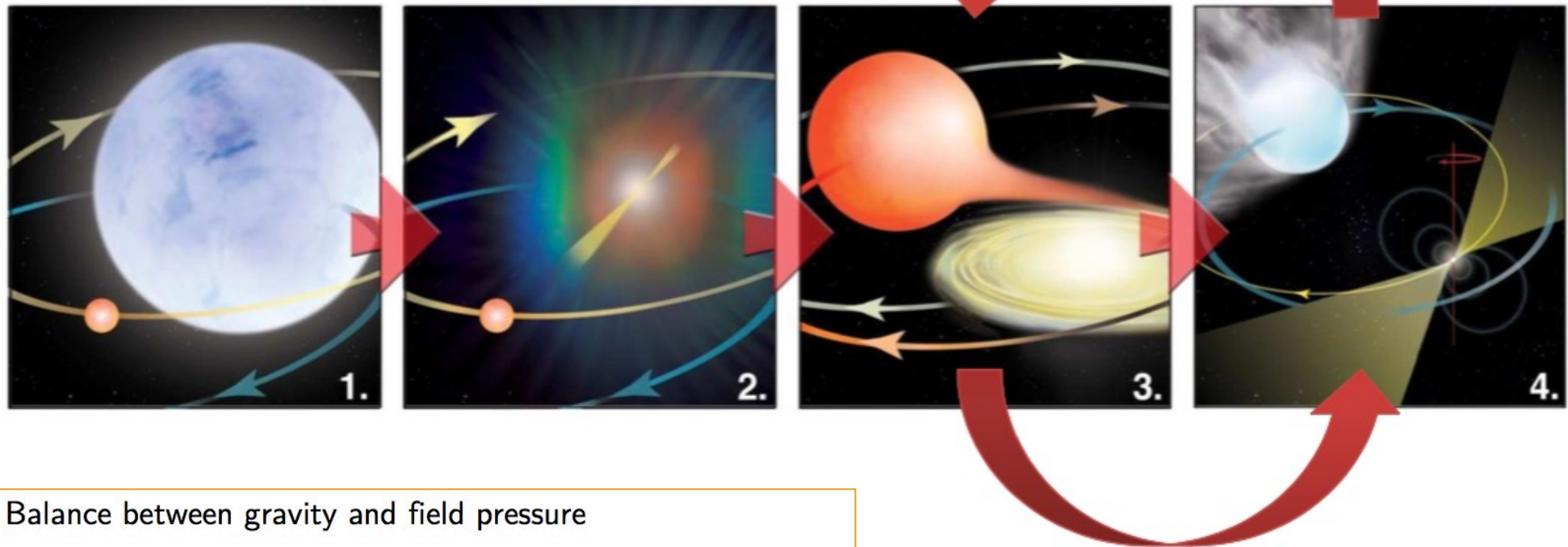


Detect gravitational waves (\rightarrow Pulsar Timing Array)

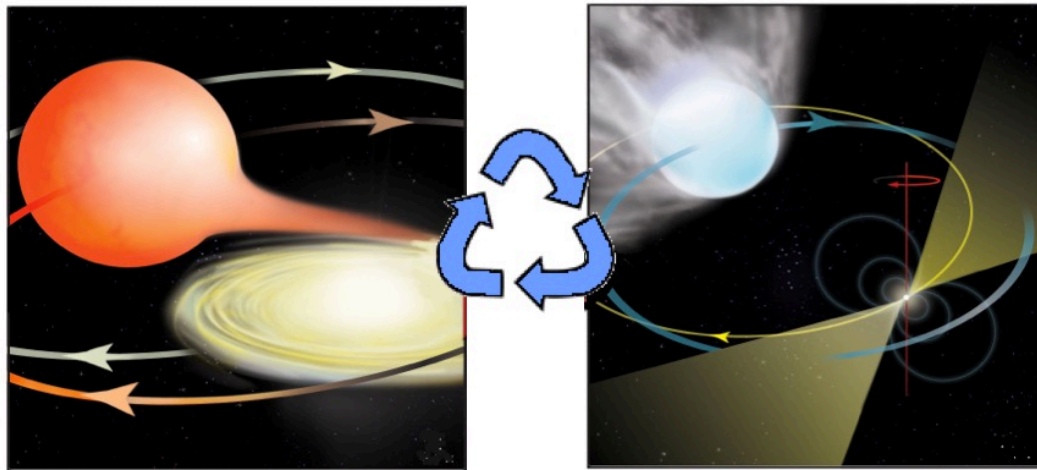
Deep space pulsar navigation



Millisecond pulsar, recycling phases



Balance between gravity and field pressure



Accreting gas accelerating the pulsar, reactivating it

How are transitions regulated

The light cylinder (the radius at which the magnetic field lines of the neutron star open up):

$$R_{lc} = \frac{cP}{2\pi} \simeq 4.77 \times 10^9 \left(\frac{P}{1s} \right) \text{cm},$$

The Alfven or magnetic radius R_m is the distance at which the magnetic field starts to dominate the dynamics of the in-falling matter.

$$\frac{B^2}{8\pi} = \frac{1}{2}\rho V_f^2.$$

This simple formula makes use of many things:

$$V_f = \sqrt{\frac{2GM_{ns}}{R}} \quad B(R) = B_{ns} \left(\frac{R_{ns}}{R} \right)^3 \quad \rho = \frac{\dot{M}_{acc}}{4\pi R^2 V_f} \quad \dot{M}_{acc}(r) = \frac{1}{4} \dot{M}_* \left(\frac{R_{cap}}{r} \right)^2 \quad R_{cap} = \frac{2GM_{ns}}{V_{rel}^2}.$$

To define the relative velocity of the neutron star with respect to the accreting matter we need to consider the kind of outflow.

We can start by using the polar wind, which is flowing at a velocity of $\sim 1000 \text{ km s}^{-1}$

$$V_w = V_0 + (V_\infty - V_0) \left(1 - \frac{R_*}{r} \right)^\beta \simeq V_\infty \left(1 - \frac{R_*}{r} \right)^\beta$$

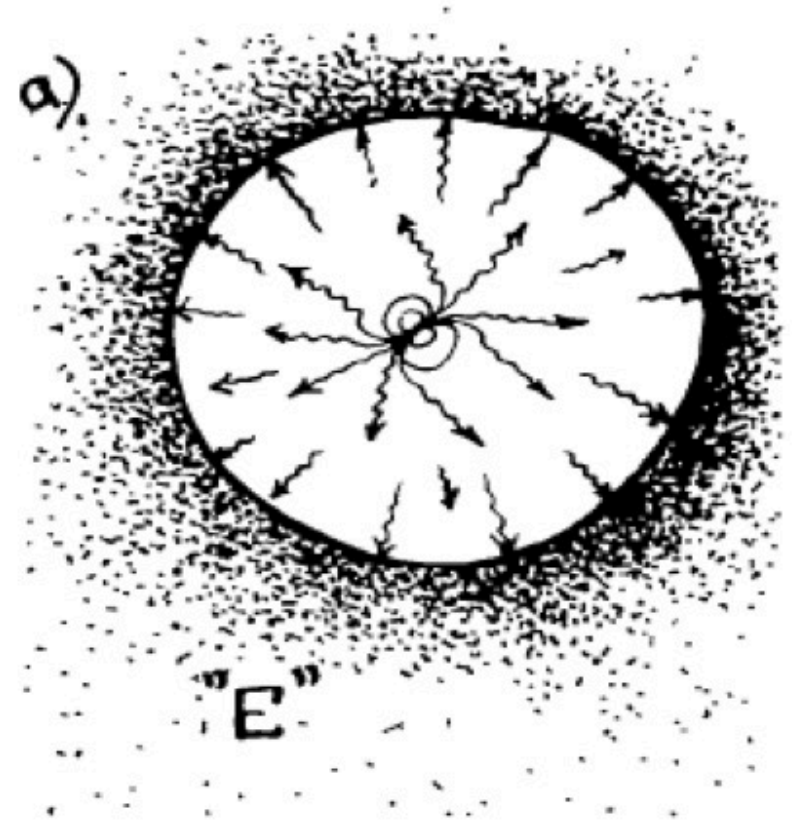
and with it, we can compute the radii of interest.

Ejector → Propeller → Accretor (and sometimes backwards)

- Interaction with the environment:

Mass within the gravitational capture radius falls towards the NS exerting a pressure

- EM pressure $>$ Matter pressure
(at the radius of gravitational capture)
for the NS to work as an ejector
- EM pressure $\sim B^2 P^{-4}$
- Matter pressure $\sim \dot{M}$
- As the NS decelerates, the matter pressure eventually overcomes the EM pressure and switches the pulsar off



Ejector → **Propeller** → Accretor (and sometimes backwards)

- Infalling matter is stopped by the pressure of the magnetosphere
(Matter pressure = Magnetic pressure)

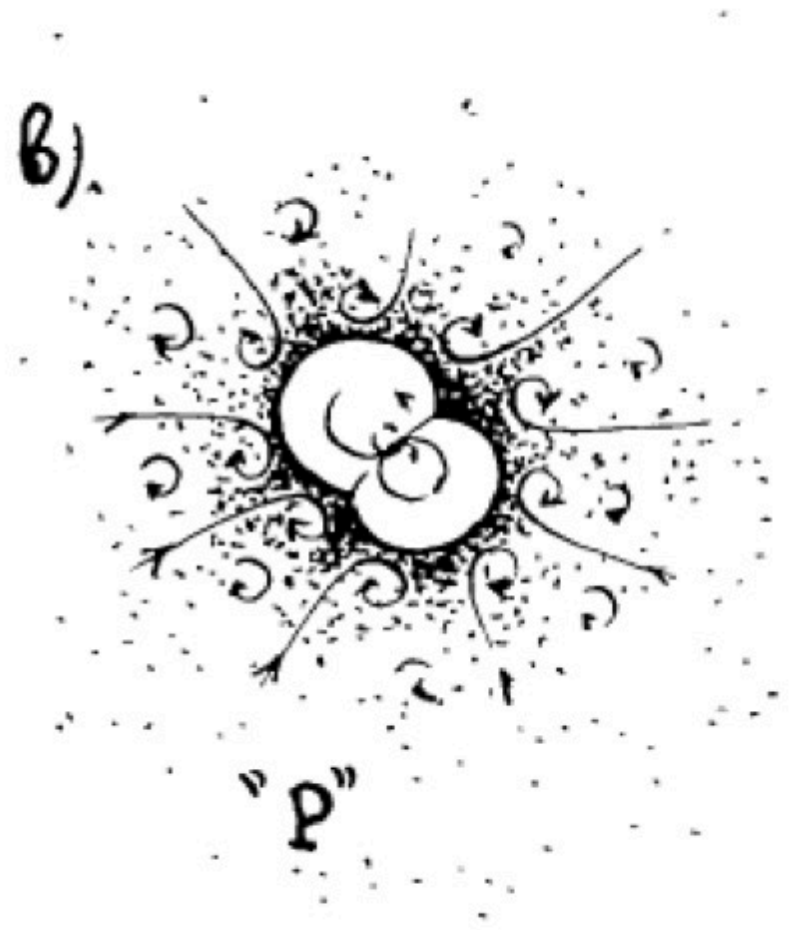
$$R_M = \frac{(B_1 R_1^3 / 2)^{4/7}}{\dot{M}^{2/7} (2GM_1)^{1/7}}$$

When $R_M < R_{LC}$ the NS abandons the ejector state

- But since the NS is a fast rotator matter cannot accrete onto the NS

$$R_{co} = \left(\frac{GM_1}{\Omega^2} \right)^{1/3}$$

- Accretion is inhibited as far as $R_M > R_{co}$



Ejector → Propeller → **Accretor** (and sometimes backwards)

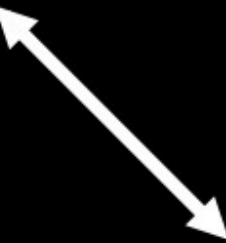
Accretion is inhibited as far as energy is released by the rotating NS to the incoming matter at a much larger rate at which the atmosphere can cool down

Only when the NS has slowed down enough that $R_M < R_{CO}$, accretion is allowed, and X-ray pulses should be observed



Accretion powered state

Bright X-ray outburst ($\sim 10^{36}$ erg/s)
X-ray pulsations



An intermediate (propeller?) state

Sub-luminous accretion ($\sim 10^{34}$ erg/s)
Brighter gamma-ray emission



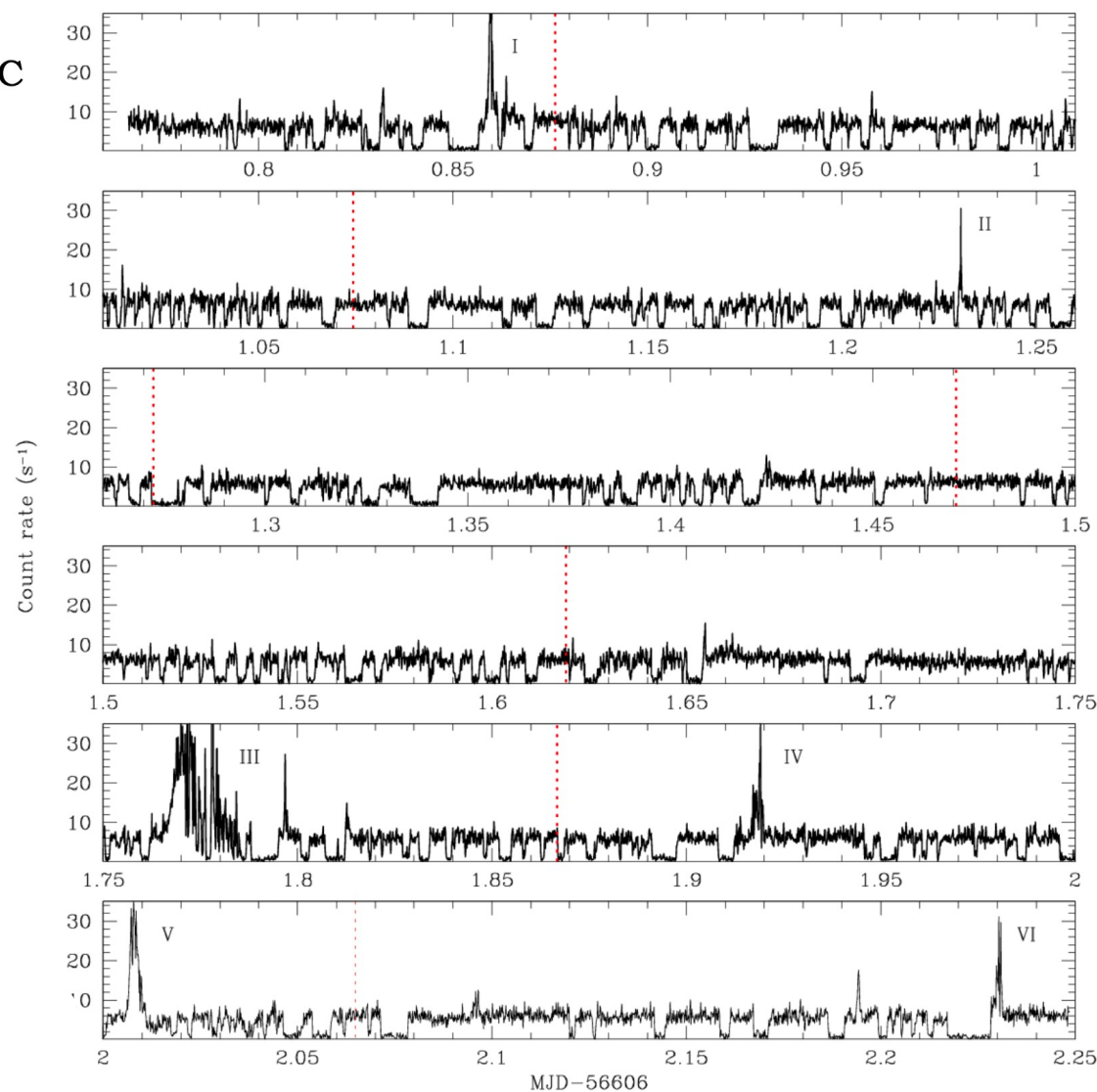
Rotation powered state

Faint in X-rays ($\sim 10^{32}$ erg/s)
Radio/gamma-ray pulsations



Transitional pulsars (an example of an X-ray obs.)

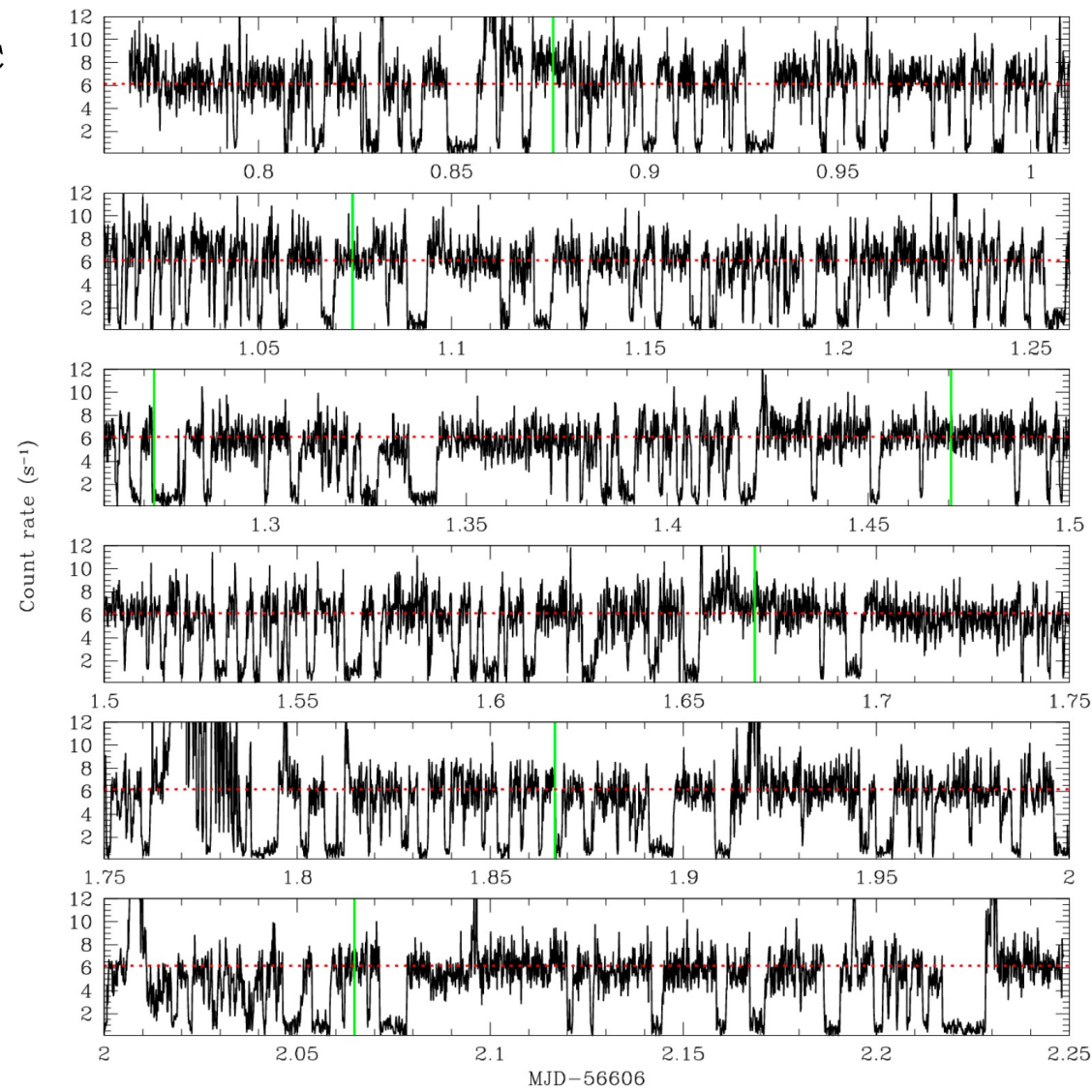
XMM-Newton EPIC
Nov 10th, 2013
134 ks



Bogdanov et al.

Transitional pulsars (an example of an X-ray obs.), zoom

XMM-Newton EPIC
Nov 10th, 2013
134 ks



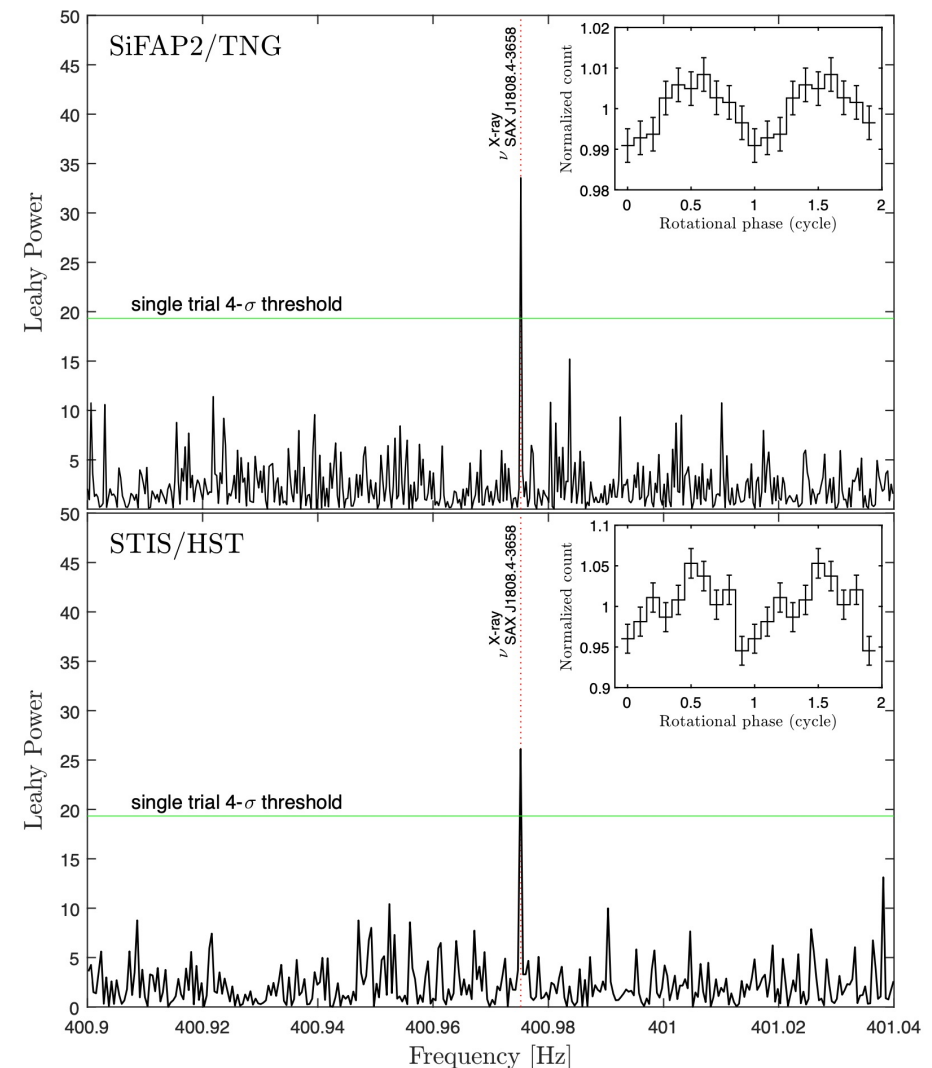
Bogdanov et al.

Not so simple.. accretion does not fully kill non-thermal pulses

The pulsar was surrounded by an accretion disk, had X-ray pulsations and its luminosity was consistent with magnetically funnelled accretion onto the neutron star.

Current accretion models fail to account for the luminosity of both optical and ultraviolet pulsations; synchro-curvature radiation in the pulsar magnetosphere or just outside of it?

Particle acceleration can take place even when mass accretion is going on.



Optical and UV pulsations at the X-ray period of the transient low-mass X-ray binary system SAX J1808.4–3658, during an accretion outburst that occurred in August 2019.



Thank you for your attention