Some issues of NS/Magnetars

小嶌康史 (広島大学)

Yasufumi Kojima/Hiroshima Univ.

途中での質問・議論　大歓迎

～中性子星の観測と理論～　研究活性化ワークショップ 2019

2019/2/18-20 京都大学

広島大学 極限宇宙研究拠点 CORE-U

Core of Research for the Energetic Universe HIROSHIMA UNIVERSITY

Contents

– Single NS –

- Species

NS species, diversity   Magnetar

- Age problem

Mag-field decay, timescale of kyrs

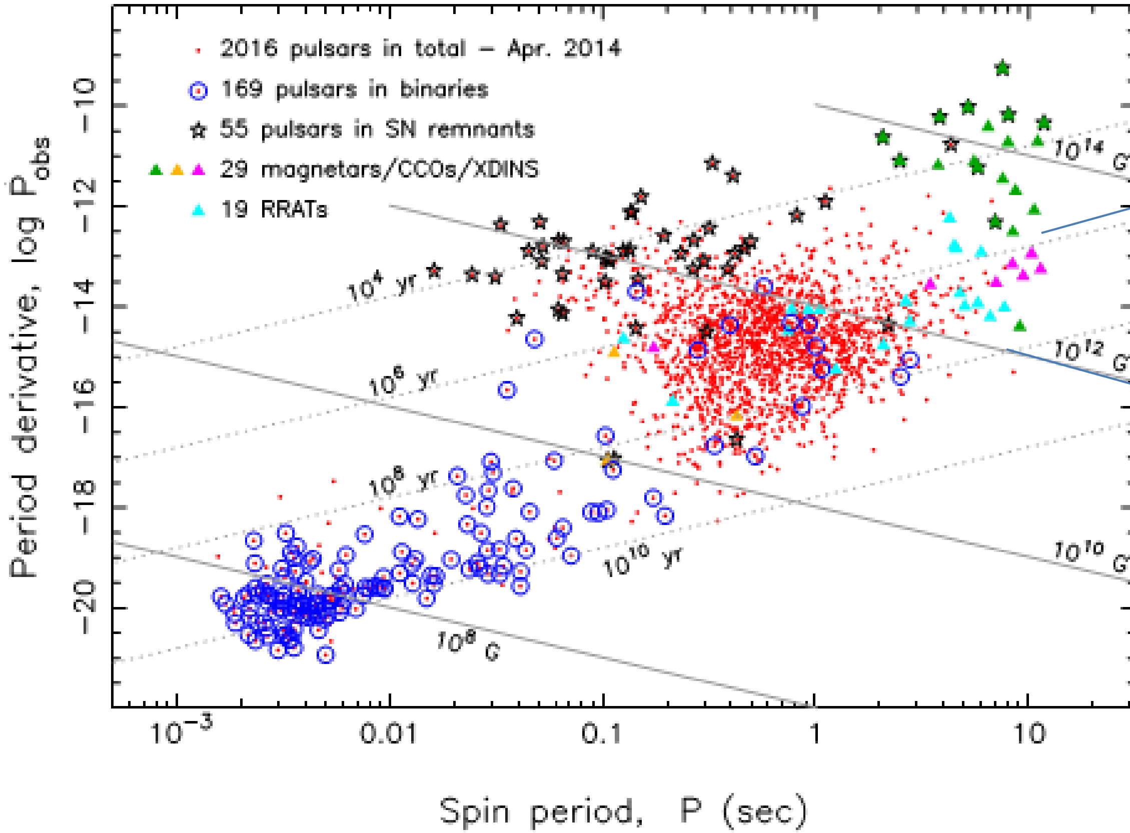
- Revolution

Magnetosphere, HE emission

- Summary

Magnetar/XDINS/CCO in P-Pdot

$$(P, \dot{P}) \Leftrightarrow (\tau_c, B_d)$$



$$\tau_c = P / 2\dot{P}$$

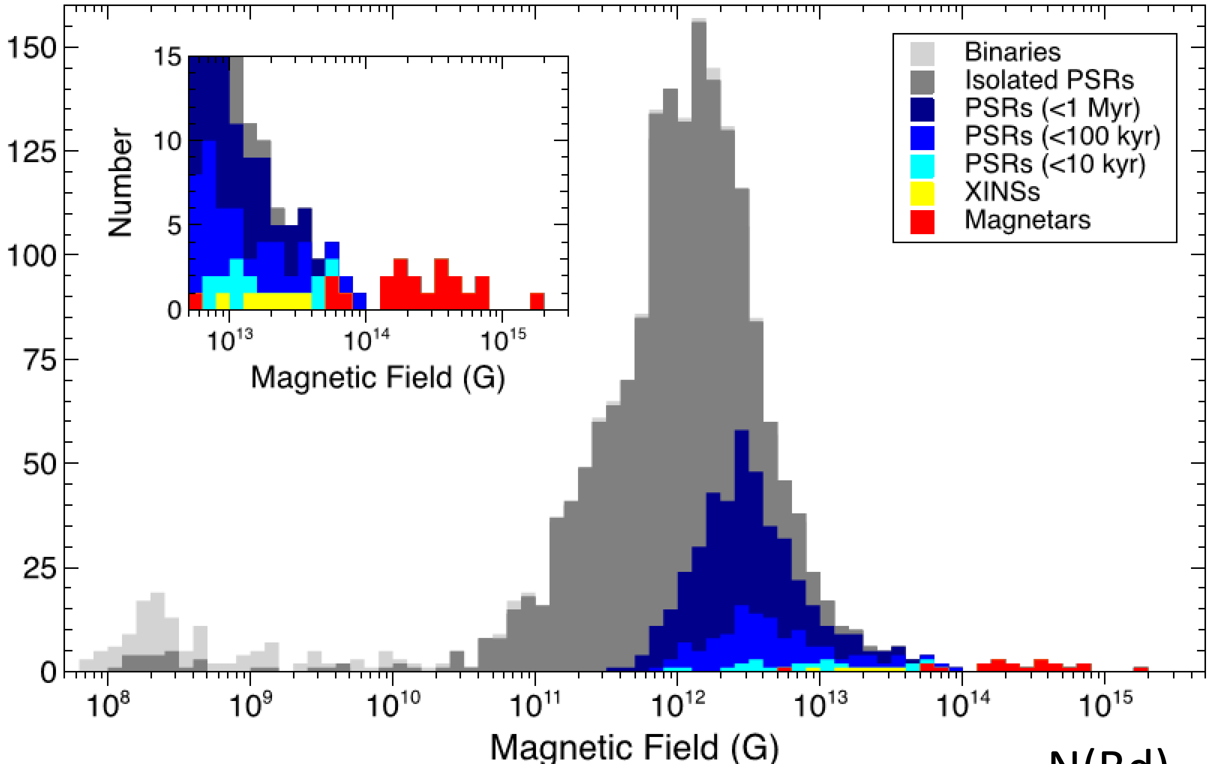
$$B_d \propto \sqrt{P\dot{P}}$$

Figure 8: P–$\dot{P}$ diagram for non-accreting pulsars (from Tauris *et al.* 2015 and using data from Manchester *et al.* 2005). Lines of constant characteristic age (dotted), $P/(2\dot{P})$, and dipole spin-down luminosity, are drawn in grey, while the main observational manifestations of pulsars are plotted with different symbols.

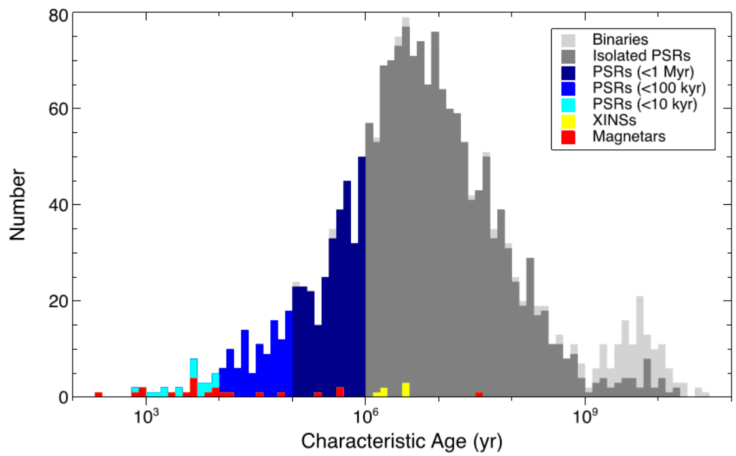
Gourgouliatos + 2018

NS Distribution

$$(P, \dot{P}) \Leftrightarrow (\tau_c, B_d)$$



N(Bd)



N(tau)

Olausen &Kaspi 2014

P(spin) & B(mag) of NS

Conservations of ang mom/mag flux amplify by a factor

$\sim 10^{10} \sim (R_f/R_i)^2$

- $P \sim P_i (R_f/R_i)^{-2} = ms - s$ Radio PSRs
- $B \sim B_i (R_f/R_i)^2 = 10^{12} G$ Radio PSRs
- $\Delta P/P \sim \Delta P_i/P_i$ $\Delta B/B \sim \Delta B_i/B_i$ Scatter of P_i , B_i ?
- SN simulation -> specific cond. Fast Rot. + Strong mag.
- Not so extreme in dynamics
- $E_k/E_g \sim 10^{-3}$ $(P/10ms)^2$
- $E_m/E_g \sim 10^{-12}$ $(B/10^{12}G)^2$

  $\sim 10^{-6}$ for magnetar $B = 10^{15}\ G$

possible up to $B = 10^{18} G$

Brief review of Magnetic White Dwarfs

- Some hints?
- Simple scaling is never allowed

$B \sim 10^3 - 10^9 G$ in WD

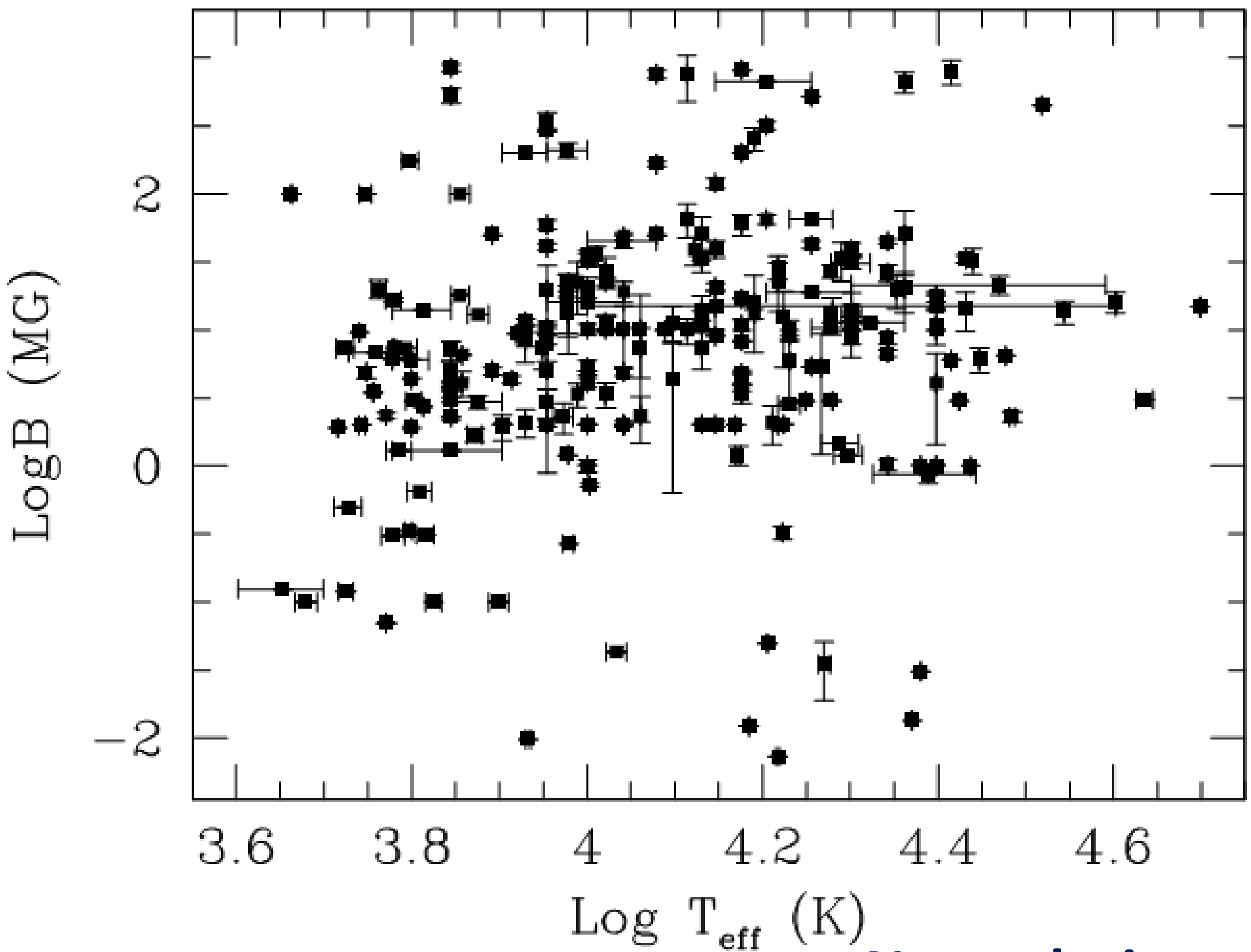
-> $\times 10^6 \propto R^{-2} = 10^{15} G$ (magnetar?)

- Numbers increased, but still inconclusive

Ref

e.g., Ferrario, L + (2015)Sp. Sci. Rev.

Quick review of mag. WD 1



$B \sim 10^9 G$

Upper limit
Real

$B \sim 10^3 G$

Lower limit?
Obs. limit

No evolution

Fig. 3 Magnetic field strength against effective temperature in MWDs showing no indication for field evolution with cooling age (this work)

Quick review of mag. WD 2 Distribution

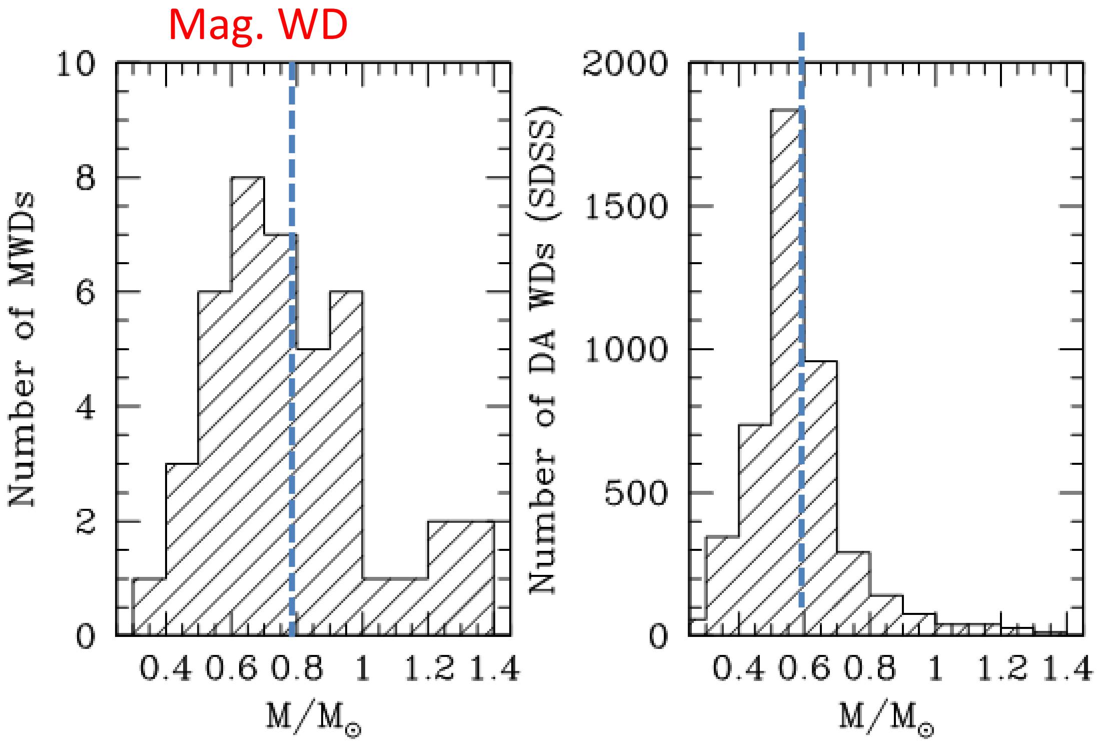
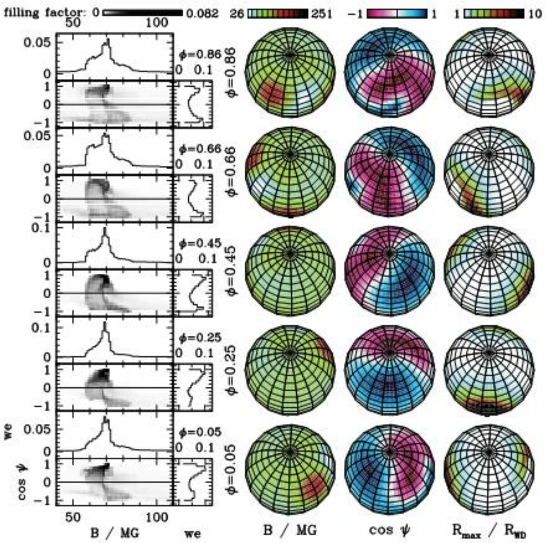


Fig. 14 Left panel: The mass distribution of MWDs (Ferrario and Wickramasinghe 2010). Right panel: The mass di...ibution of non-magnetic DA WDs from SDSS (Kepler et al. 2007).

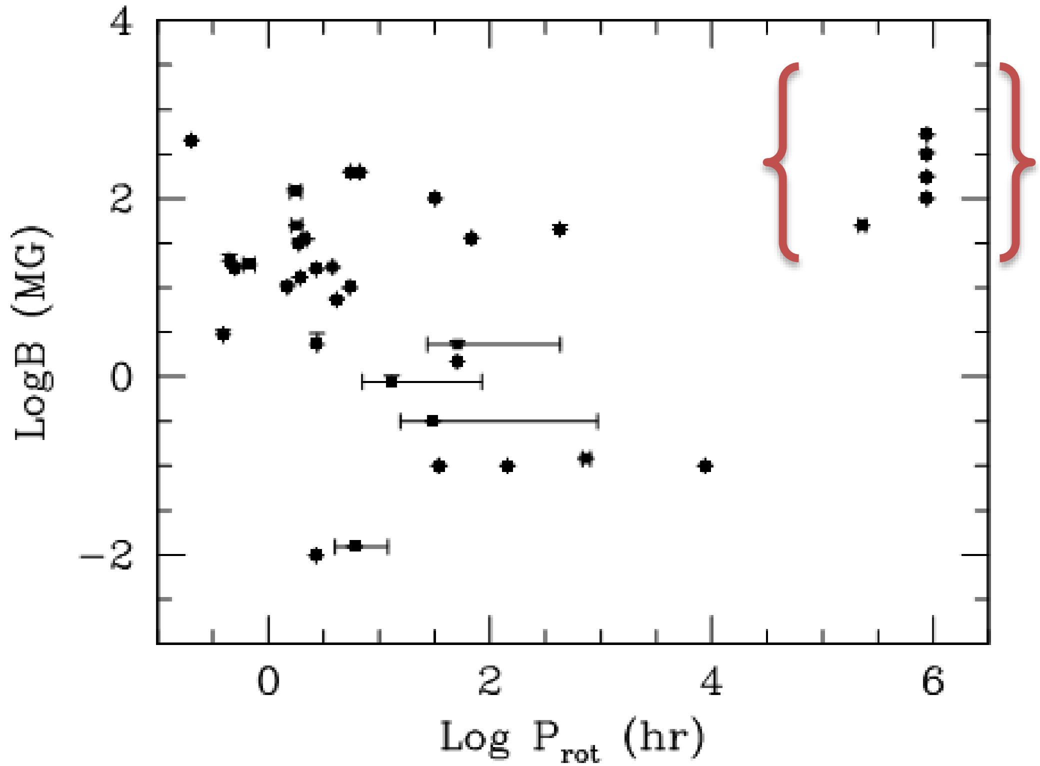
More massive mag. WD

+ Complex non-dipolar B field?

(time-resolved spectropolarimetry)



Quick review of mag. WD 3
B vs P



Two classes?

{ Slow+ strong }

Another

Implications

Progenitor of MWD

No correlation MWD and Binary(non-degenerate star)

Mechanism still under debate

✓ Fossil

✓ Dynamo (differential rot....-> strong B)

in common envelope at merging phase (hypothesis)

-> massive?, non-dipole?

Summary of this part

MS -> WD (B$\sim 10^6 G$) unknow high end

MS -------> NS (B$\sim 10^{12} G$)

a general picture

Mag. +dynamo? B$\sim 10^{15} G$

CCO. +fall back? B$\sim 10^{10} G$

Progenitor of magnetar &
Origin of magnetic fields

- Associated with SNR? Information of progenitor

  Yes / No

- Massive progenitor ? CXOUJ1647102

  But light? SGR1900

-> inconclusive

Theoretical interest: Conditions for dynamo action

Massive or not fast or slow at birth

-> multipole field generation ?

->Observation of Polarization?

New era?

Evolution of Neutron Star Magnetic Fields: The Emperor Wears No Clothes

D. Q. LAMB
Department of Astronomy and Astrophysics
and Enrico Fermi Institute
University of Chicago

Frontiers of X-ray astronomy 1991

ABSTRACT

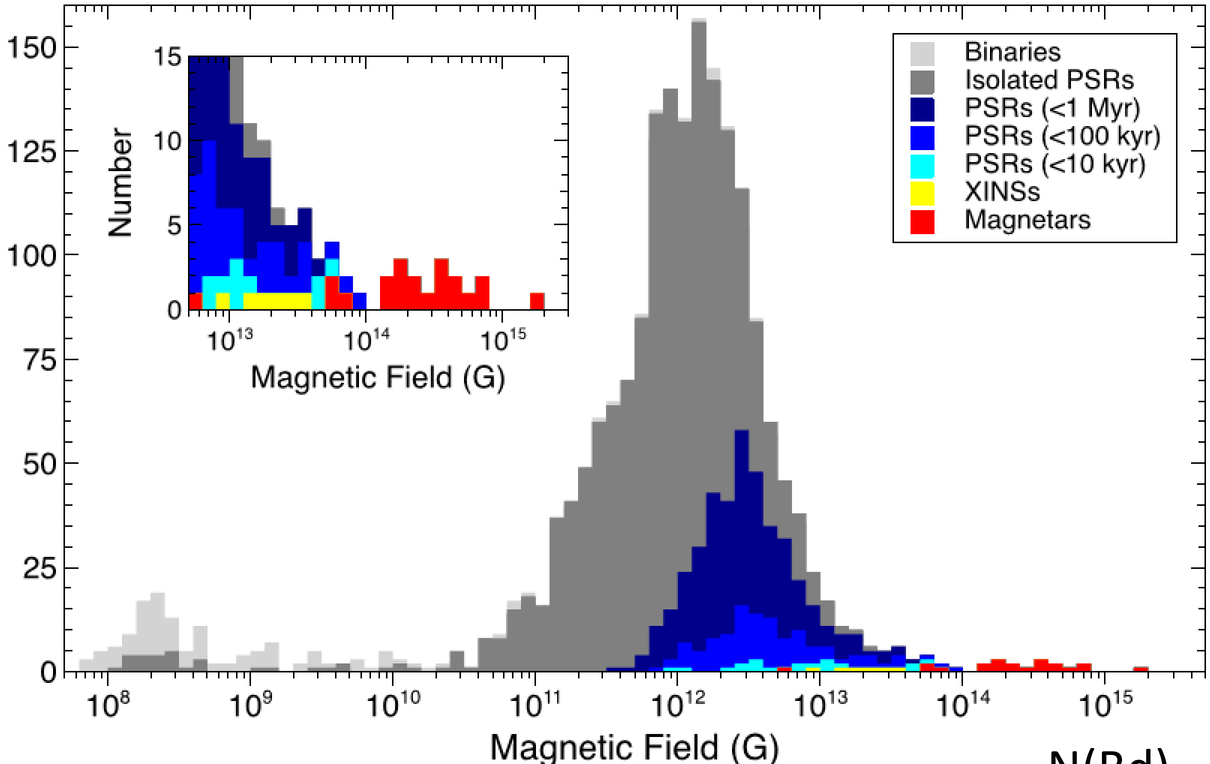
For many years, conventional wisdom has held that neutron stars are born with strong magnetic fields which then decay exponentially with time. We review estimates of the magnetic fields and ages of accretion-powered pulsars, rotation-powered pulsars, γ-ray burst sources, and low-mass X-ray binaries. We re-examine the evidence for exponential field decay, which comes primarily from observations of rotation-powered pulsars, and find it wanting. We mention new observations which suggest that the magnetic fields of some neutron stars decay little or not at all. We conclude that little is known about how neutron star magnetic fields evolve.

NS Distribution

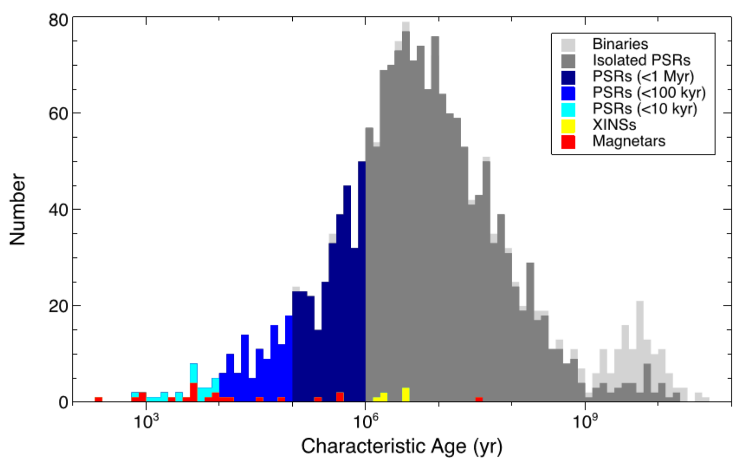
$$(P, \dot{P}) \Leftrightarrow (\tau_c, B_d)$$

Yes!

New era!



N(Bd)



N(tau)

Magnetic field evolution is NOT established in PSR, but …

Magnetic field decay in MAGNETARS

✓ Age problem :

$\tau_c > \ t_{age} \approx \ t_{SNR}$

-> High resolution Spectroscopy for SNR age

AXP 1E 1841-045 (Kes 73) AXP 1E 2259+586 (CTB 109)
CXOU J171405.7-381031 (CTB 37B) SGR 0526-66 (N49)
SGR 1627-41 (G337.0-0.1)

field decay or a slow rotator at birth

$$\tau_c \equiv P_0/2\dot{P}_0 = (\int_0^{t_0} K dt + P_{ini}^2/2\ )/K(t_0) > t_0$$

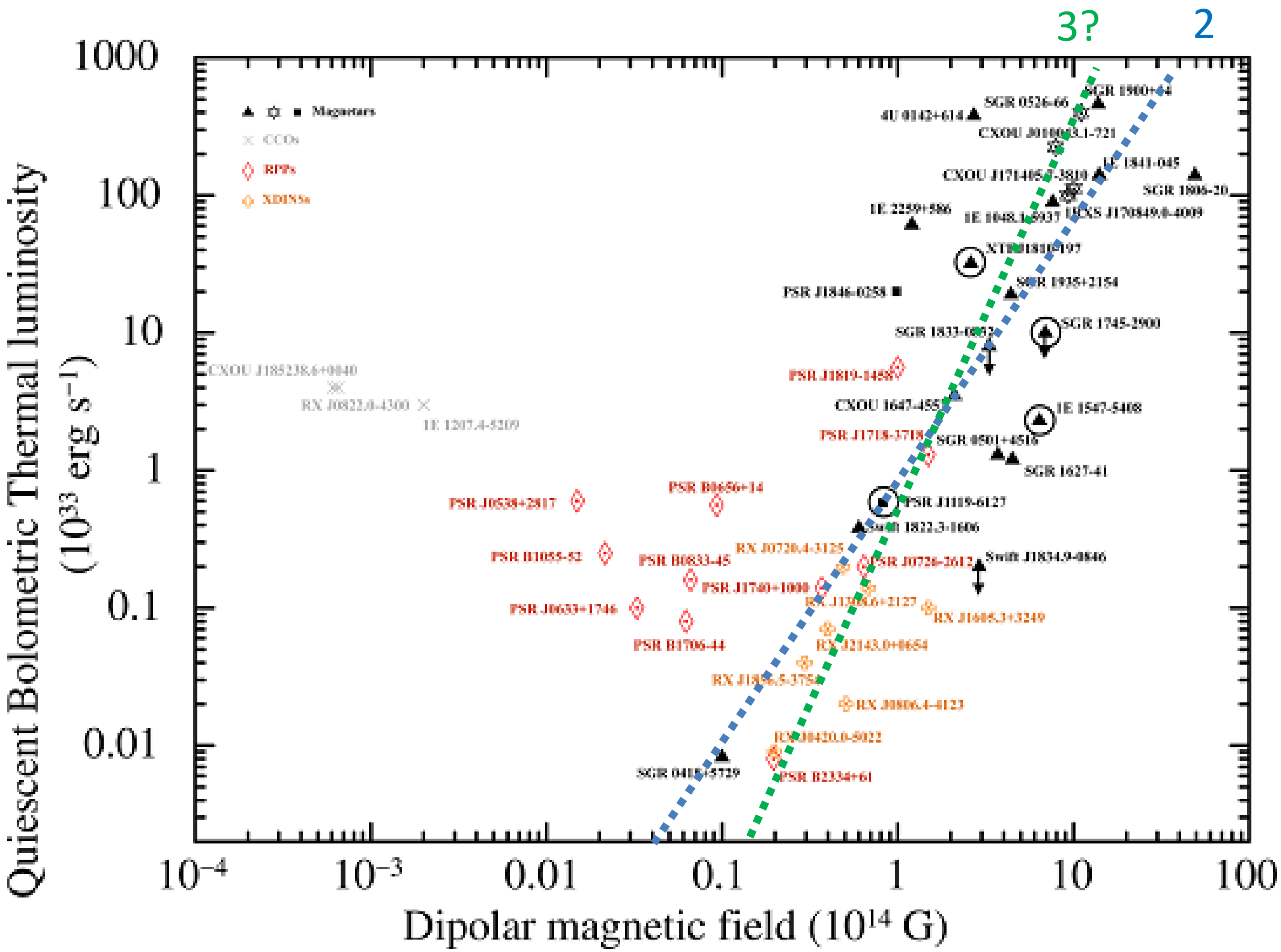
✓ Thermal luminosity excess

->Magnetar activity

$$L_x t \approx 10^{35}(erg/s)\, 10^4 y \approx 10^{46} erg \approx \Delta E_{mag}(B_{14.5})$$

✓ Luminous for stronger one? $\propto B_p^a \quad a > 2?$

Lx-Bp diagram Coti Zelati et al(18) MN



$$L_x \propto B_p^2 \quad \propto dE_{mag}/dt \quad \rightarrow B_p^a \quad a = 2, 3?$$

Timescale

What determines an appropriate timescale?

$$t = 10^3 - 10^5 y$$

Many theoretical models (a few below)

- ?Core

Microphysics Gusakov+(17)

A model Ofengeim+(18)

- ?Crust

$$\tau_H = 4\pi e n_e L^2 / cB_0 \approx 10^3 (L_{0.1km})^2 (B_{15})^{-1} yrs$$

-> Coupling with magnetosphere

Akgun+(17,18)

- Multipoles?

- After magnetar activity, evolution to XDIN?

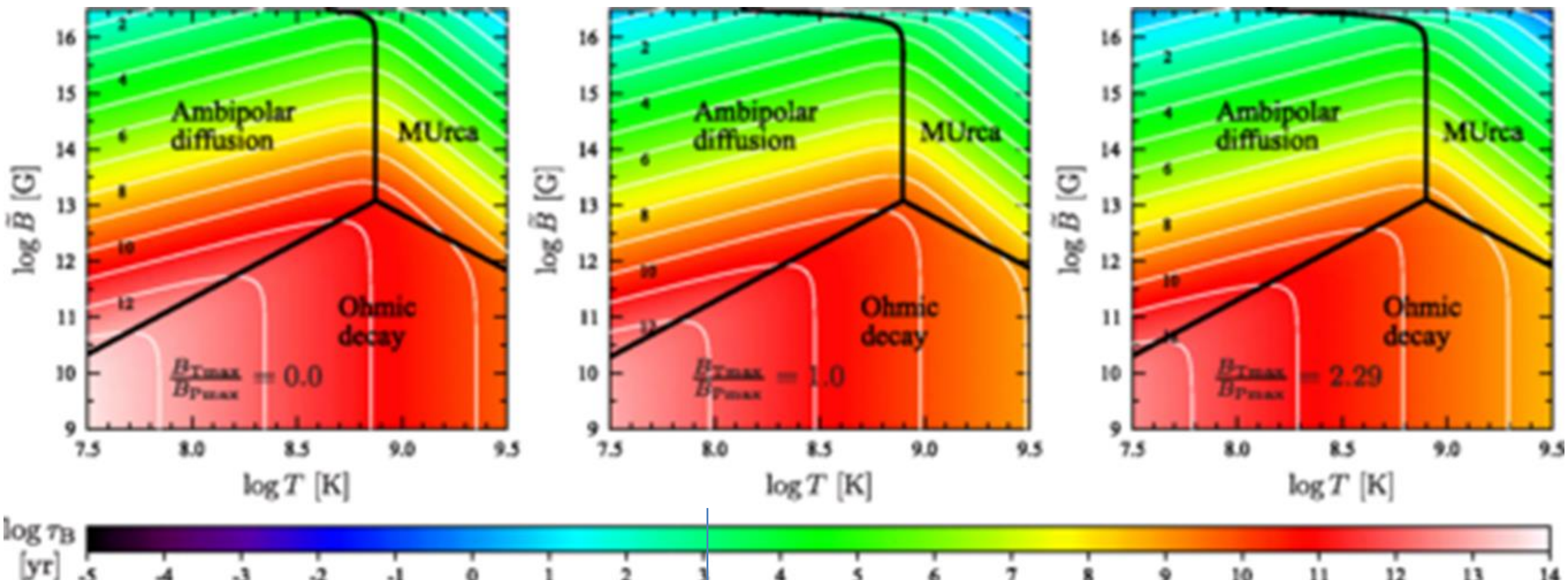
Decay time scale of magnetic fields in core I

M. E. Gusakov, E. M. Kantor, and D. D. Ofengeim

Phys. Rev. D **96**, 103012

Possible mechanism

$t \propto B^{-2}$



T<1kys

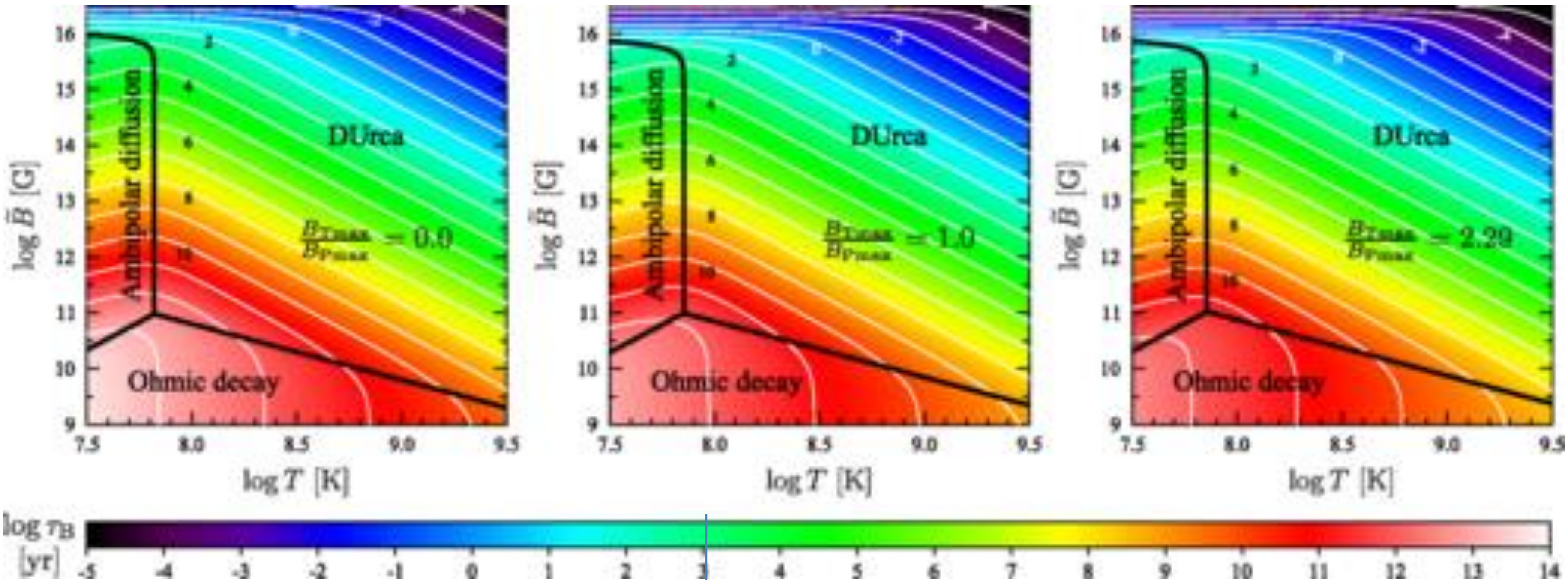
Modified URCA

$$n + n \rightarrow n + p + e + v$$
$$n + p + e \rightarrow n + n + v$$

Decay time scale of magnetic fields in core II

M. E. Gusakov, E. M. Kantor, and D. D. Ofengeim

Phys. Rev. D **96**, 103012



T<1kys

Direct URCA

$$n \to p + e + v$$
$$p + e \to n + v$$

D. D. Ofengeim and M. E. Gusakov(18)
Phys. Rev. D **98**, 043007(18)

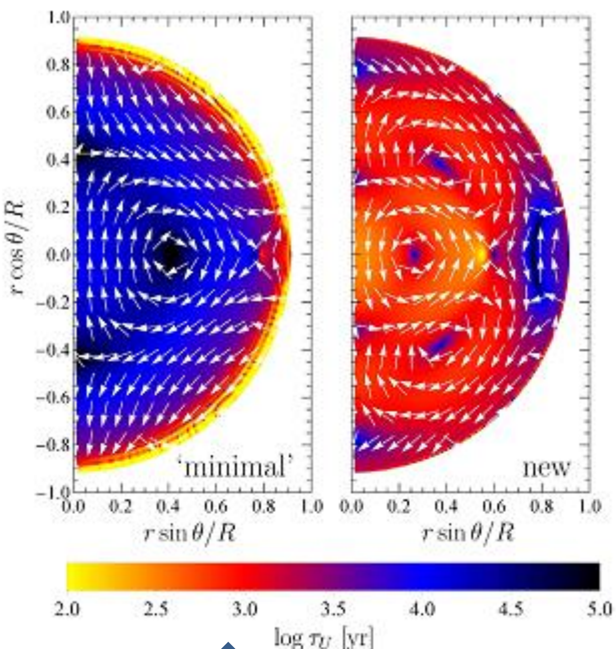


FIG. 11. Density plot showing the logarithm of the time scale τ_U (in yr) for the minimal model of the magnetic field from Sec. IV A (left panel) and for the model with no particle flows through the crust-core interface from Sec. IV D (right panel). Arrows indicate direction of the derivative $\partial \boldsymbol{B}/\partial t$ given by Eq. (56). To plot the figure we assumed $B_{max} = 5 \times 10^{15}$ G and $\bar{T} = 2 \times 10^8$ K.

1kyrs

Result depends on
initial setup

$$v = 10^{-6} cms^{-1}$$
$$= 10^{-4} kmyr^{-1}$$

$$\partial_t \delta B = -\nabla \times \delta E$$

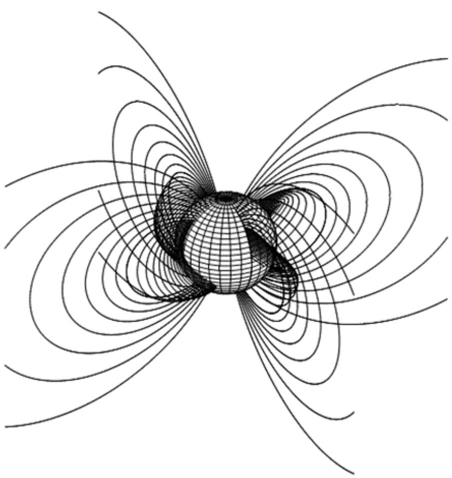
$\delta\mu$
fluctuation

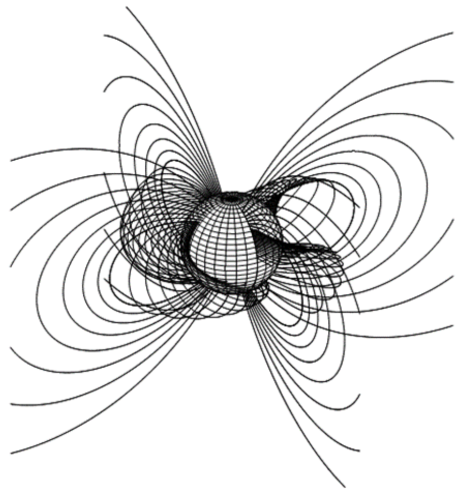
Coupling between crust and magnetosphere

3

Long-term evolution of the force-free twisted magnetosphere of a magnetar

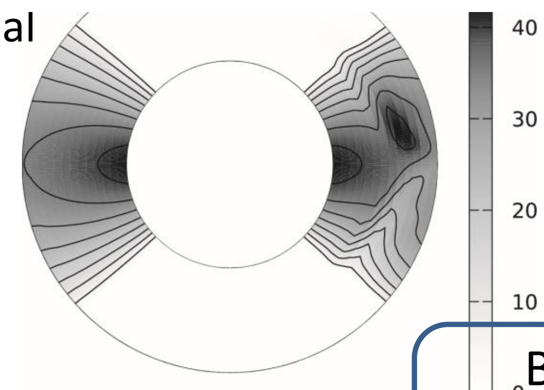
Akgun + Mon Not R Astron Soc. 2017;472



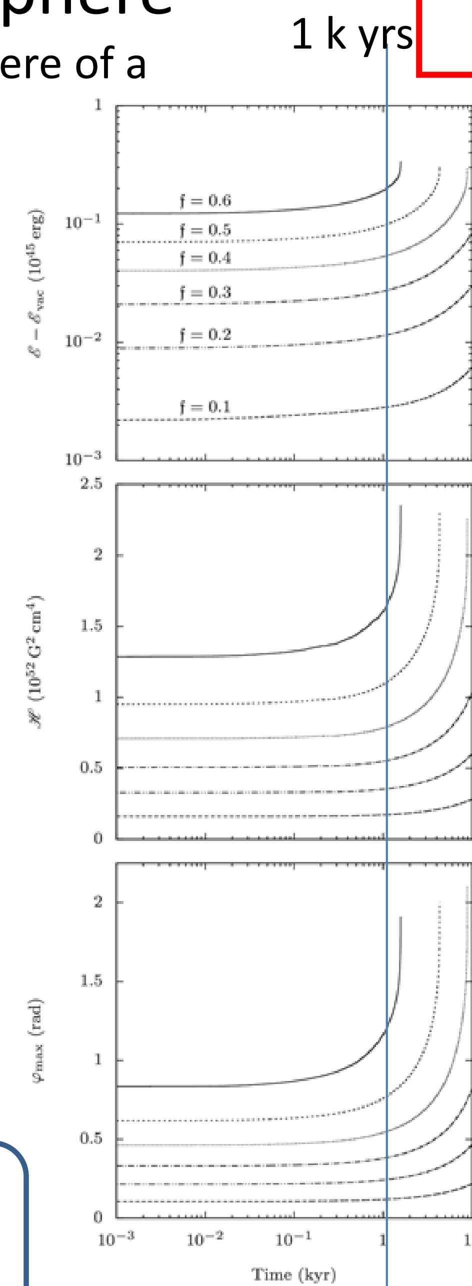


Initial

10^3 yrs



Crust enlarged for display



Burst/Flare

$\Delta E \approx 0.4 \times E_{ms,14}$

$\approx 10^{44} erg$

Comment

- ? Explosion at 1kyrs

  E=10^44 ergs @Bs=10^14G

- Or breakdown of the model

Burst/Flare

$\Delta E \approx 0.4 \times E_{ms,14}$

$\approx 10^{44} erg$

?BC at interface

?Initial model

?...

Wrong estimate

Theoretically Impossible

$$\Delta E = E_{max} - E_{vac}$$

Open field for $\frac{\Delta E}{E_{vac}}$ >0.66

$$\Delta E_{Burst} \approx E - E_{open}$$

Magnetosphere

Developing of numerical study of magnetosphere

Classical picture

Stationary + axisymmetric

Revolution!

Present

3D+TD +GR +multipole

FFE (MHD)

Spitkovsky(06), Kalapotharakov+(12)…

PIC

Ab initio simulation

[Shibata+(07)…] Philippov+(15)…

Ex

Recent works
PIC / FFE

THE ASTROPHYSICAL JOURNAL, 851:137 (10pp), 2017 December 20 Gralla, Lupsasca, & Philippov

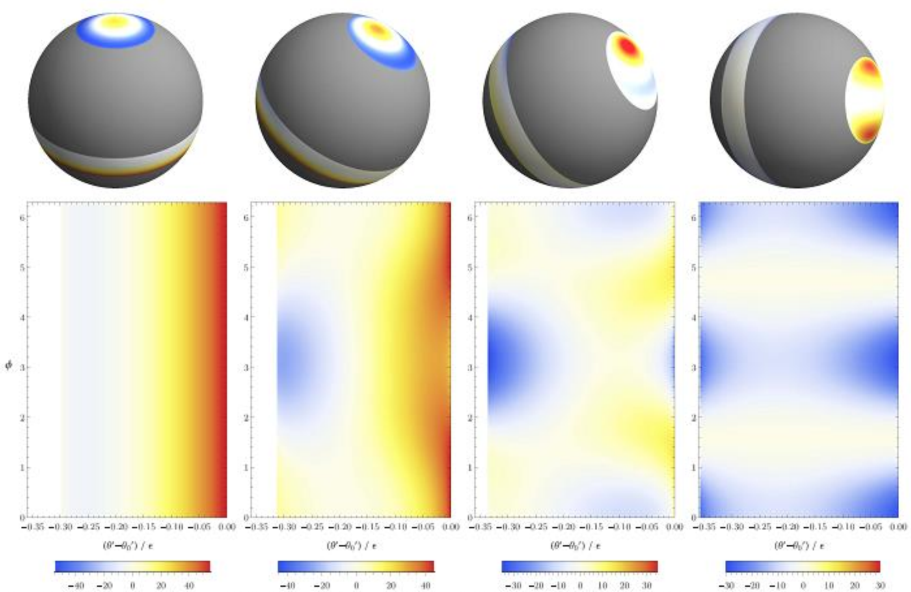


Figure 3. Polar cap structure for the quadrudipole pulsar with the quadrudipole-to-dipole ratio $q = 3$, moment of inertia $\mathcal{I} = 2/5$, and compactness $\mathcal{C} = 1/2$. From left to right, we display inclinations $\iota = \{0°, 30°, 60°, 90°\}$. The color map corresponds to the charge-current norm $J^2 R_*^2/(\epsilon B_1)^2$, as described in Figure 1. In the top row, we show the distribution on the sphere (gray means zero charge and current), with the polar caps made artificially large (by scaling with the relative area kept invariant) for illustration purposes. (The area of each cap scales as ϵ. Even for the fastest rotating pulsars, with $\epsilon \sim 1/5$, the southern cap would be only 3° wide.) In the bottom row, we show a zoomed-in view of the annular southern polar cap with ϵ scaled out. The southern edge of the cap lies at an angle $\theta' = \theta_0' \approx 109°$. 3D animations are available here https://youtu.be/M_ruTbM8YNo.

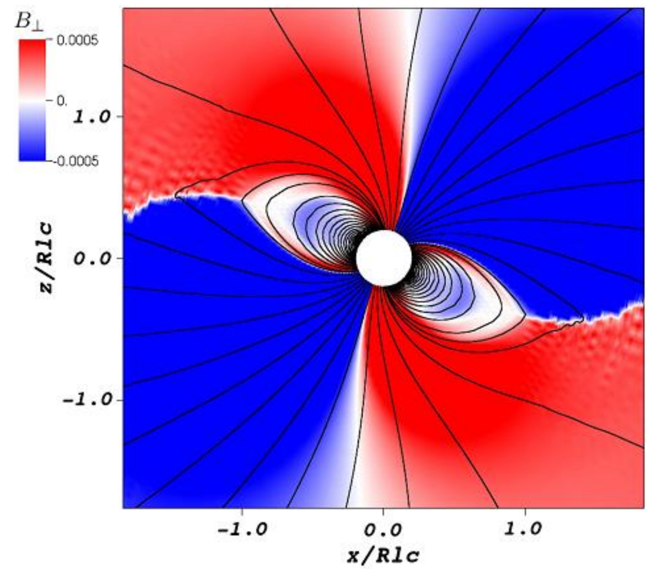


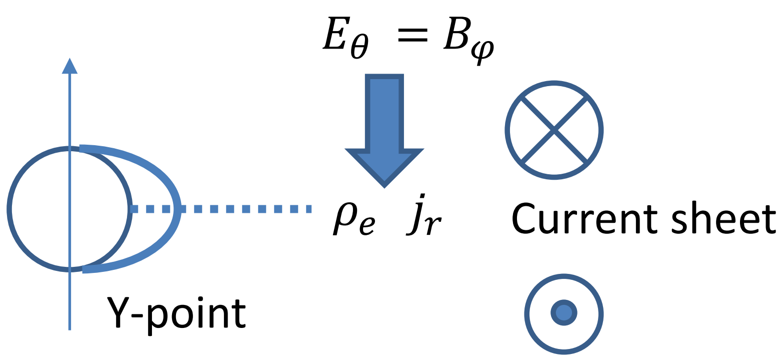
FIG. 8. *Misaligned rotator.*—Poloidal and toroidal magnetic field obtained with $v_s = 0.2$ and misalignment angle $\chi = 30°$. Lines z represents the magnetic field in the $\mu - \mathbf{\Omega}$ plane, whereas the color scale corresponds to the magnetic component perpendicular to the plane.

Philippov +ApJ(17)
PIC+multi B+GR

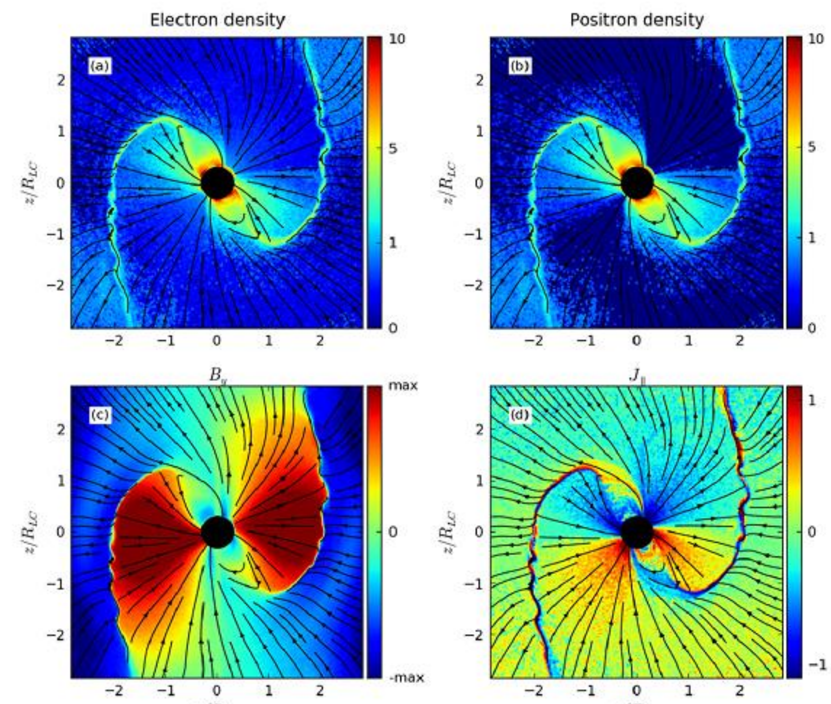
Carrasco +PRD(18)
FFE +GR

Regular, better?

Singular->pathology?



Philippov +15 PIC



New trend

- Singularity -> magnetic reconnection->
  new emission region!
- Checked by Observation
  Phase-resolved spectroscopy

EM structure & Luminosity

Split-monopole

$<B_\varphi> = <E_\theta> = -B_L \omega R_L^2 r^{-1} sin^1\theta$

$4\pi <P_{em}> = (B_L \omega R_L^2)^2 r^{-2} sin^2\theta \rightarrow L = B_0^2 \omega^4 R^6 \times \frac{2}{3}$

Magnetic dipole rotator in vacuum

$4\pi <P_{em}> = (B_L \omega R_L^2)^2 r^{-2} \quad sin^2\theta sin^2\alpha$

$\rightarrow L = B_0^2 \omega^4 R^6 \times \frac{1}{6} sin^2\alpha$

Mag. Quadrupole $<P_{em}> \propto sin^2\theta cos^2\theta$

FFE model(numerical sol.)

$<B_\varphi> = <E_\theta> \approx -B_L \omega R_L^2 r^{-1} sin^2\theta \times ..$

$4\pi <P_{em}> \approx (B_L \omega R_L^2)^2 r^{-2} sin^4\theta$

$L \approx B_0^2 \omega^4 R^6 \times (\frac{1}{4} + \frac{1}{4} sin^2\alpha \quad)$

Maybe a mixture of …

Concluding Remark

New era

GW Astron. -> M, R, EOS

SKA -> Increasing PSRs

Different species of NS?, evolutionary track ?

✓Individual sources and theory

✓Activating gathering

are important

Thank you