Magnetic energy stored in relativistic force-free magnetosphere

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Physics of Neutron Stars – 2017

50 years after

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Energy Storage
Interior vs Exterior

$$\Delta E_{EM} \approx 10^{46} ergs$$
$$E_B \approx 10^{48} ergs$$

Two possible sits of energy storage for magnetar flares

- Crust/Core
- Magnetosphere (This talk)

Emergence/Twisting
-> Magnetic eruption

Similar to solar flare

Energy stored by twist of magnetic fields

Sudden eruption, when it exceeds a critical value

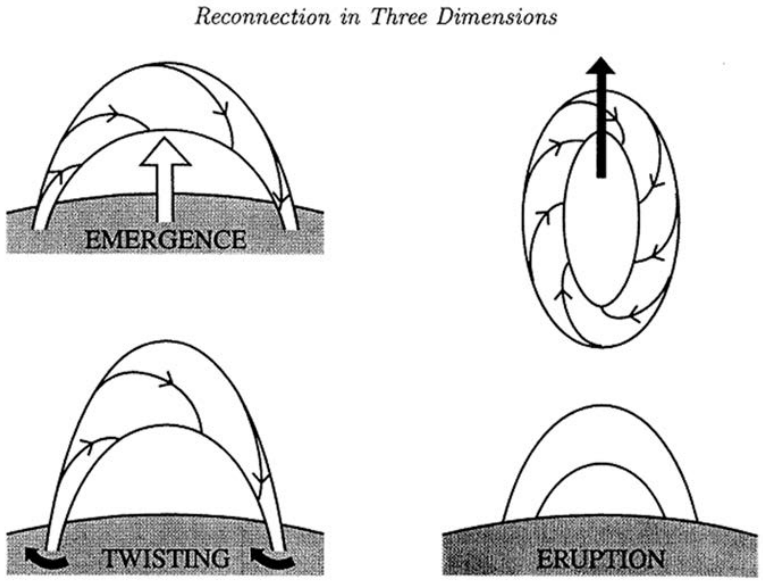


Fig. 8.17. Magnetic helicity changes associated with emergence of flux through a boundary or twisting motions at the boundary or a magnetic eruption.

Priest & Forbes "Magnetic reconnection" (2000)

GR effect ?

Force-Free Magnetosphere

Low-beta-plasma in magnetosphere

$$(B_{15})^2 \approx 10^8\, g/cm^3 > \rho c^2 >> p$$

Force-free cond. $\vec{j} \times \vec{B} = 0 \Rightarrow \vec{j} \,//\, \vec{B}$

Nonlinear partial diff eqn. (GS eqn.)

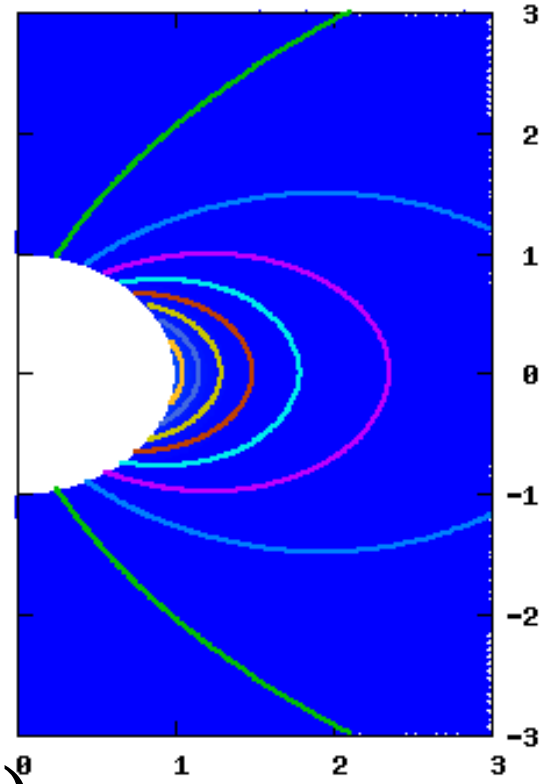
$$\Rightarrow \quad D(G) = -SS' \qquad (= -\gamma G^n)$$

Present model

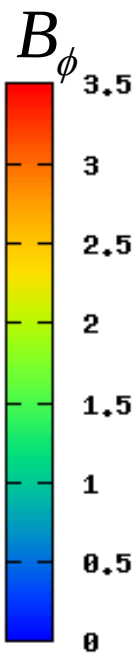
G: Magnetic flux/Poloidal comp. $A_\phi \Leftrightarrow (B_r, B_\theta)$

S: Current stream/Toroidal comp $B_\phi \Leftrightarrow (j_r, j_\theta)$

Quasi-static evolution
A sequence of equilibrium solutions



(r,θ) plain



Axisymmetric model

YK(2017) arXiv:1703.02273 :MNRAS 468

Increasing twist in a long timescale >> dynamical one

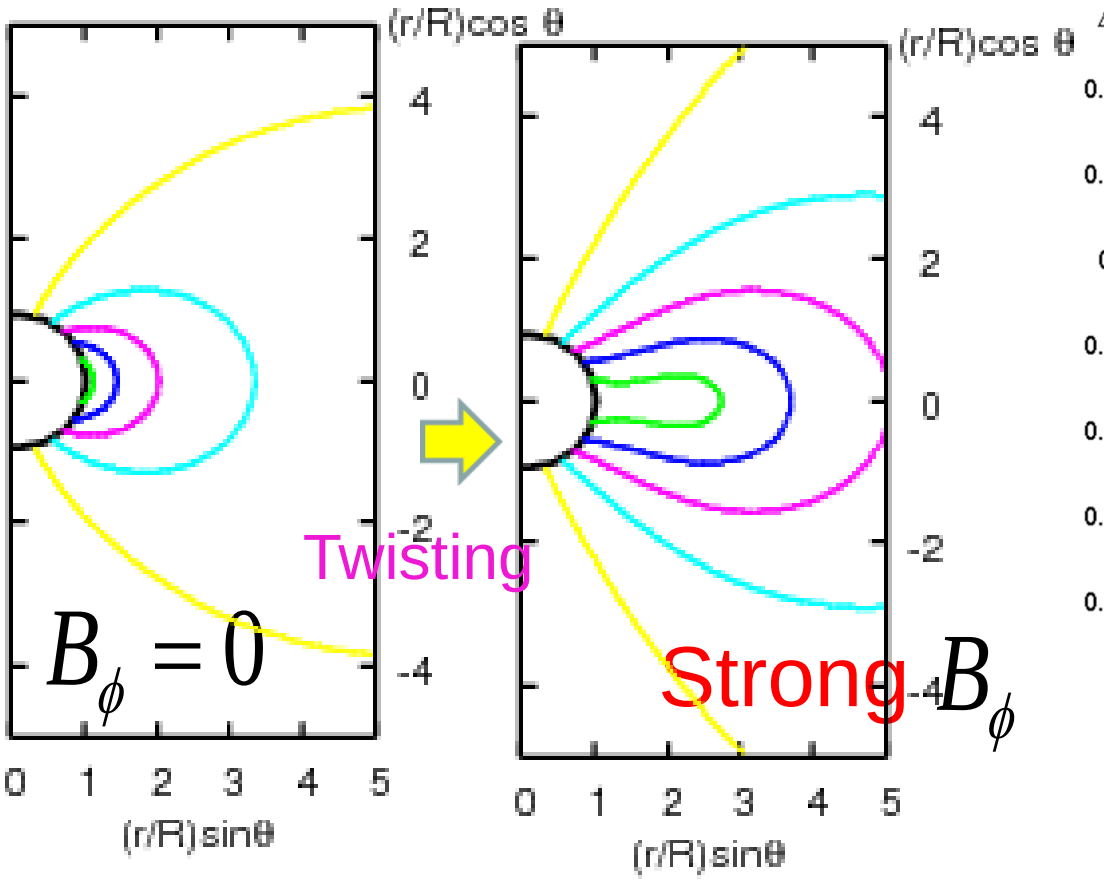
A flux rope detached

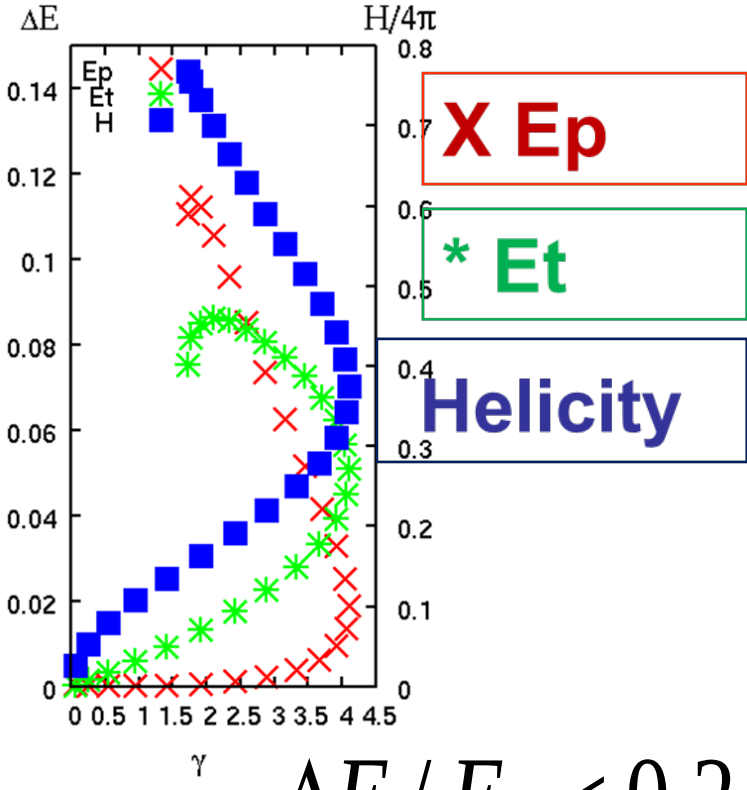
G Magnetic field lines

Model of n=7 and M/R=0.25

Dynamical simulation e.g, Parfrey et al 2013

Results in flat spacetime





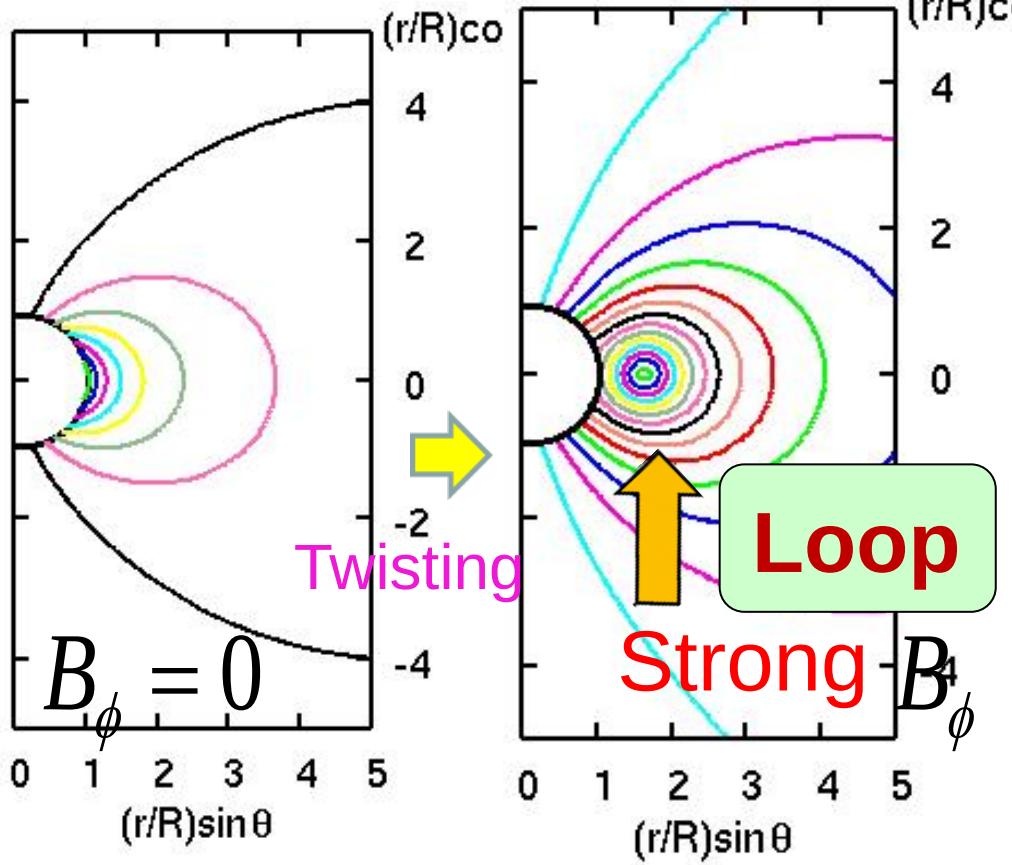
$\Delta E / E_0 < 0.2$

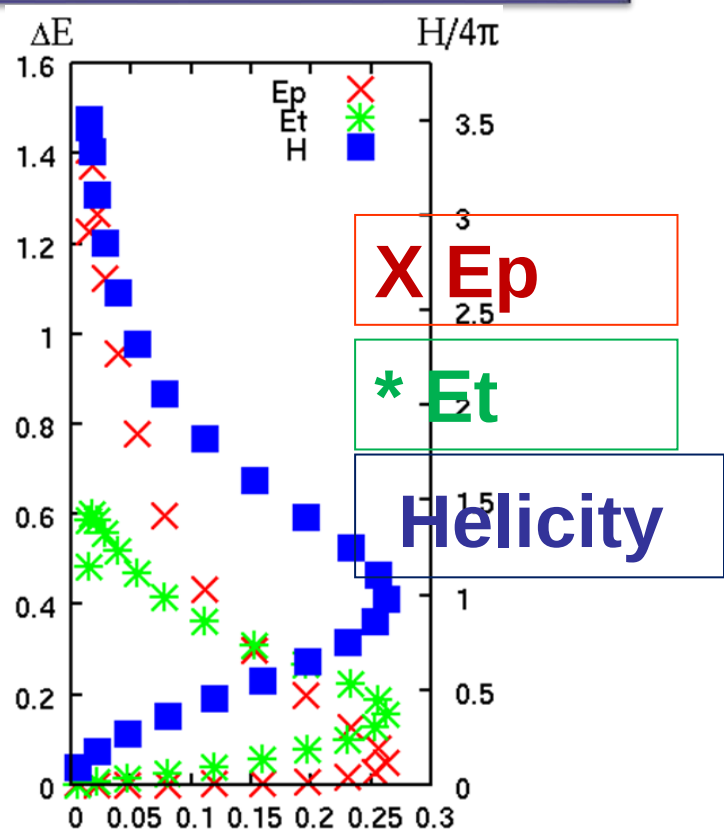
Pure dipole

Highly twisted structure with n=7

Flat spacetime

Magnetosphere in relativistic model





$$\left(\Delta E / E_0\right)_{\max} \approx 2$$

Pure dipole

Highly twisted structure with n=7

In curved spacetime M/R=1/4

Equilibrium and Maximum

- Two kinds of equilibrium

  E_t increases, E_p is const

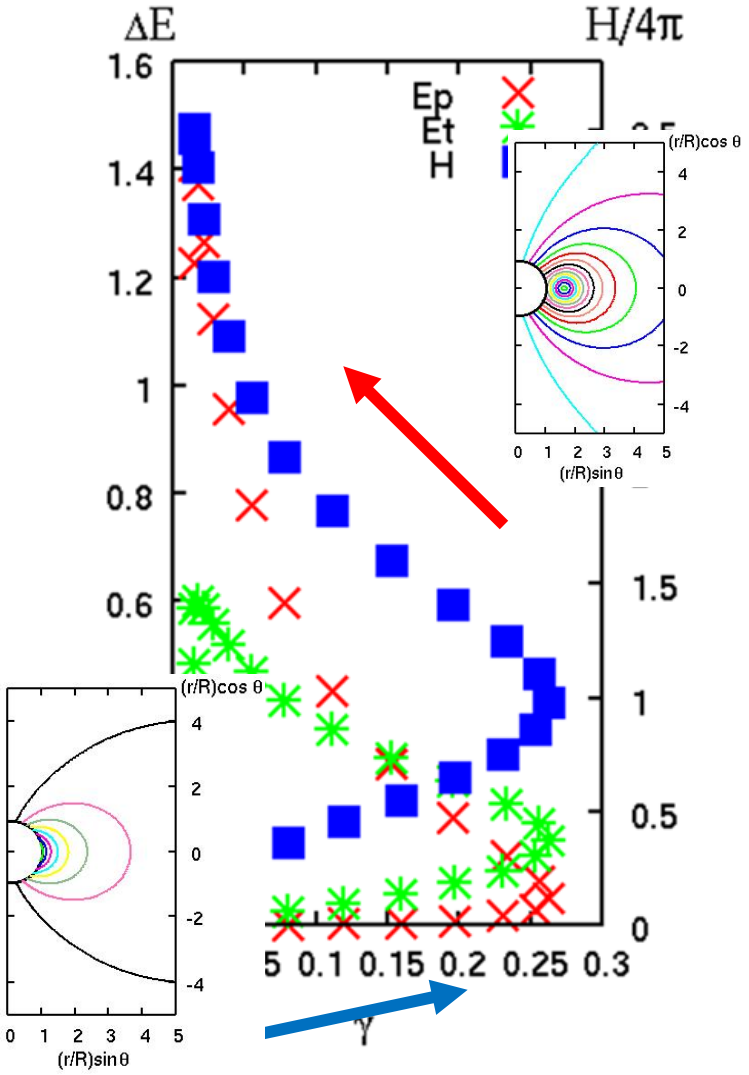
  E_p greatly increases

  -> a new structure

- Maximum in $H(\propto \Delta\varphi)$

  Highly twisted state

  -> eruption



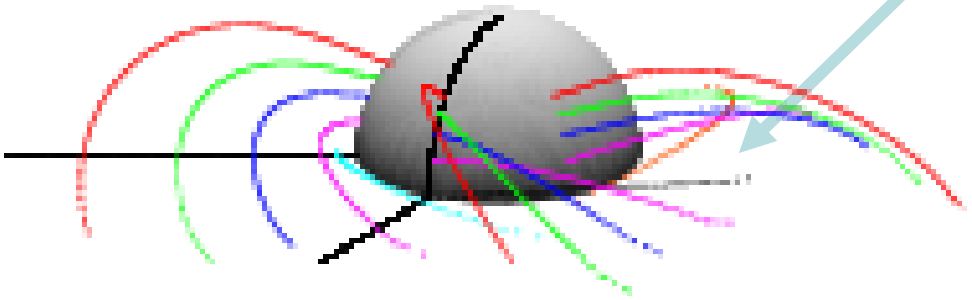
3D structure

Twisted structure $\Delta\varphi \approx 1 rad.(\approx 60^o)$

'Flux rope' near a star

Magnetic field lines around hemisphere

Flux rope at r/R=1.5



Twisted angle $\Delta\varphi \approx 1 rad.(\approx 60^o)$

Summary and Discussion

- Formation of flux rope in a relativistic system
- Larger energy stored in Magnetosphere

Flat	curved
$\Delta E / E_0 < 0.2$	$(\Delta E / E_0)_{\max} \approx 2$
$\Delta E < 10^{47}\, ergs$	$\Delta E \approx 10^{48}\, ergs$

- Maximum helicity (or twisted) state
- Transition between two states => Flare?

Relativity is important in magnetars, and the expulsion of magnetized flux rope is related to their activity.

Thank you very much.