中國科學院雲南天文台
YUNNAN ASTRONOMICAL OBSERVATORY CHINESE ACADEMY OF SCIENCES

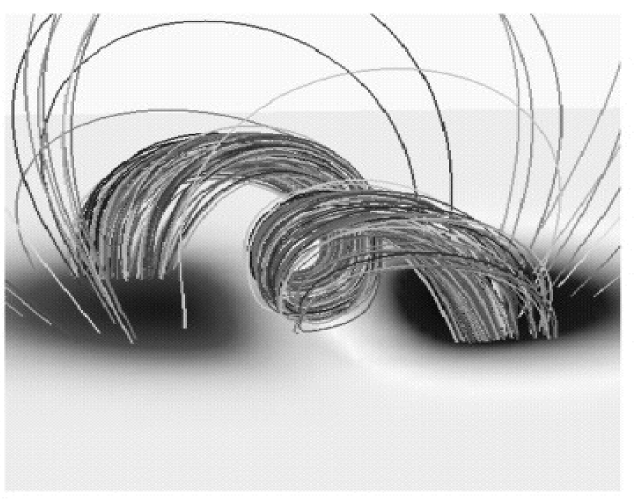
Relativistic Reconnection Driven Giant Flares of SGRs

Cong Yu（ 余聪 ）
Yunnan Observatories

Collaborators：Lei Huang
Zhoujian Cao

Outline

- Relevant Background
- Catastrophic Behavior of Flux rope



ture

- Reconnection Driven Giant Flares
- Conclusion

What is Magnetar ?

Magnetic+Star => Magnetar

Energy source : magnetic field

persistent emission & sporadic burst

Ultra-strongly magnetic field due to the dynamo amplification

Duncan & Thompson, 1992, ApJ

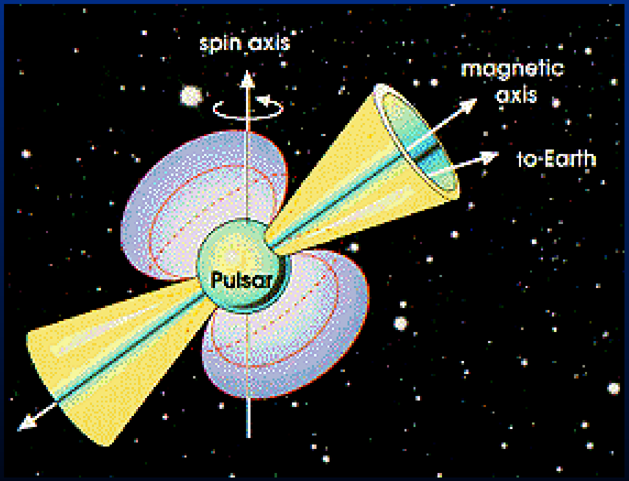
Thompson & Duncan, 1995, MNRAS

Basic Facts about Magnetars

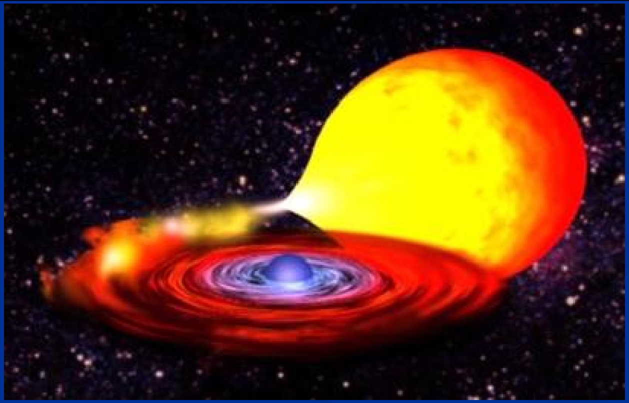
- Slow Rotation : **typically 5 – 12 s**
- Fast spin-down rate : $\mathbf{10^{-11}}$ **s s**$^{-1}$ **(cf. $\mathbf{10^{-15}}$ s s**$^{-1}$ **)**
- Young objects: **1000 – 10000 yrs**
- Typical spin-down power: $\mathbf{10^{32-33}}$ **ergs/s**
- Persistent emission: $\mathbf{10^{35-36}}$**ergs/s, 0.5-10 Kev**
- Short Bursts: **0.01-1s,** $\mathbf{10^{41-42}}$**ergs/s,**

Main manifestations of Neutron Stars:

- **(Radio) Pulsars** -
  Powered by rotational energy



- **Accreting X-ray binaries** -
  Powered by gravitational energy



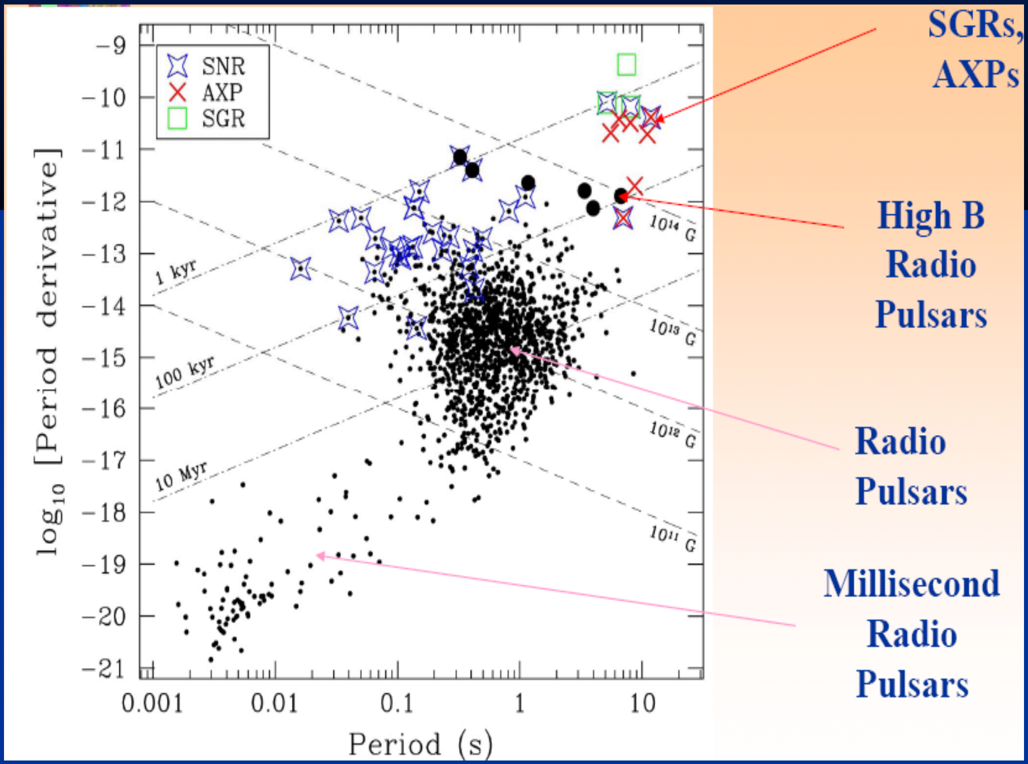
Magnetars do not fit in these two

Persistent luminosity 10-100 times higher than spin down power
-> rotational energy ruled out

$$\left|\frac{\partial}{\partial t}\int\frac{B^2}{8\pi}\,dV\right| \gg \left|I_{\rm ns}\Omega_{\rm ns}\dot{\Omega}_{\rm ns}\right|$$

Recurrent flares reach 10^{41} erg/s ~ 1000 L_{Edd} , giant flares 10^{44} erg/s ~ 10^6 L_{Edd}
-> accretion energy ruled out

How Strong Magnetic Field is in Magnetars ?



$$-\dot{E}_{\rm rot} = \dot{E}_{\rm d} = \frac{B_0^2 r_0^6 \Omega^4}{6c^3}$$

$$B_0 = 6.4 \times 10^{19} \sqrt{P\dot{P}}\,\mathrm{G}$$

Magnetars B = 10^{14} – 10^{15} G

Typically, NS B = 10^{9} - 10^{12}G powered by accretion/rotational energy

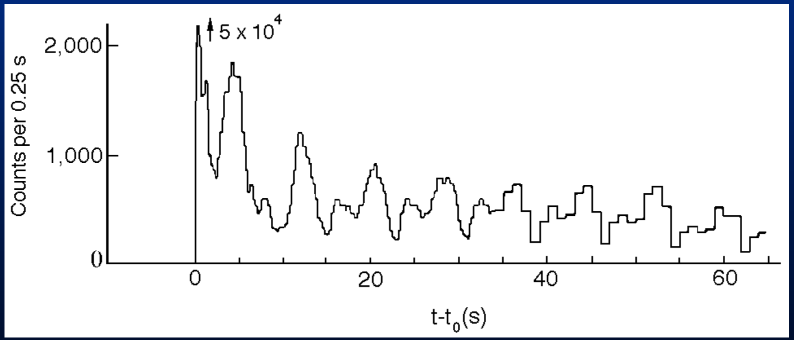
cf. the strongest man-made B-fields:
~ 5 x 10^{5} G (steady)
~ 10^{7} G (for a few microsecond)

Giant Flares

1979 March 5 – SGR 0526-66

L_{peak} ~ 4 x 10^{44} erg/s

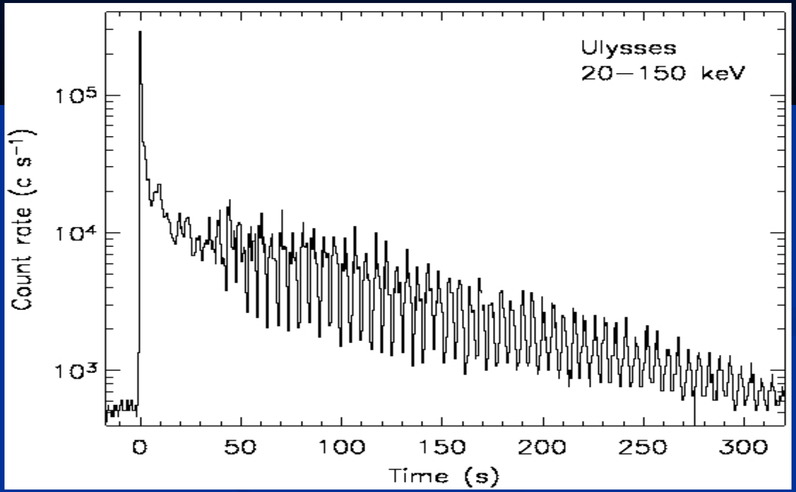
E_{TOT} ~ 5 x 10^{44} erg



1998 August 27 – SGR 1900+14

L_{peak} > 8 x 10^{44} erg/s

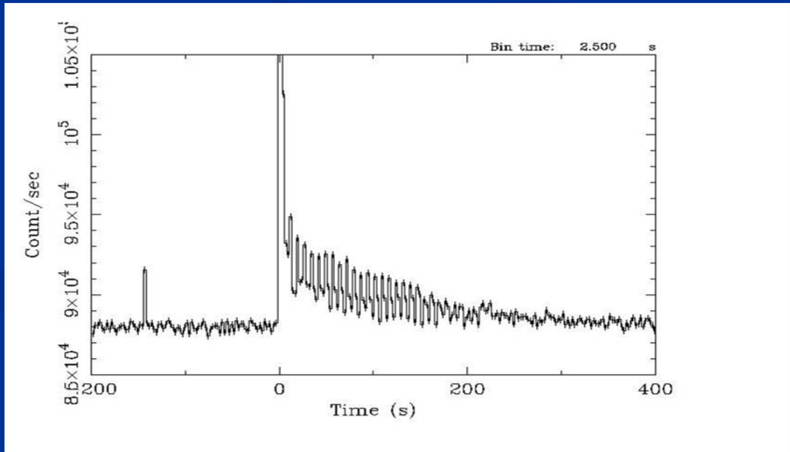
E_{TOT} > 3 x 10^{44} erg



2004 December 27 – SGR 1806-20

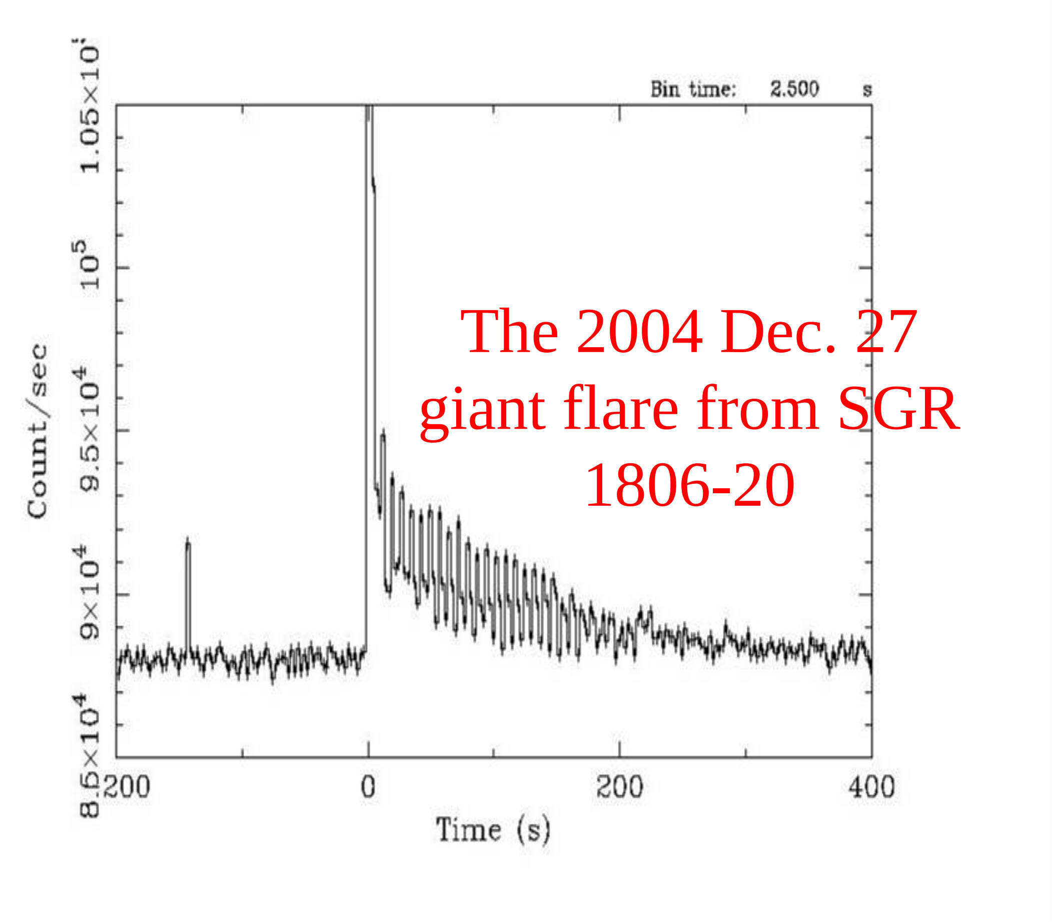
L_{peak} ~ 2-5 x 10^{47} erg/s

E_{TOT} ~ 2-5 x 10^{46} erg



Giant Flares

- Initial spike: $\Delta t \sim 0.3$ s , $E_{iso} \sim$ a few$10^{44\text{-}46}$ erg
  - hard spectrum
  - ~ ms rise time
- Pulsating tail
  - Lasts a few mi
  - Modulated at t NS rotation per
  - Softer spectru



Energy Release Mechanisms

Physical processes by which the energy is released remains one of the great puzzles in magnetars.

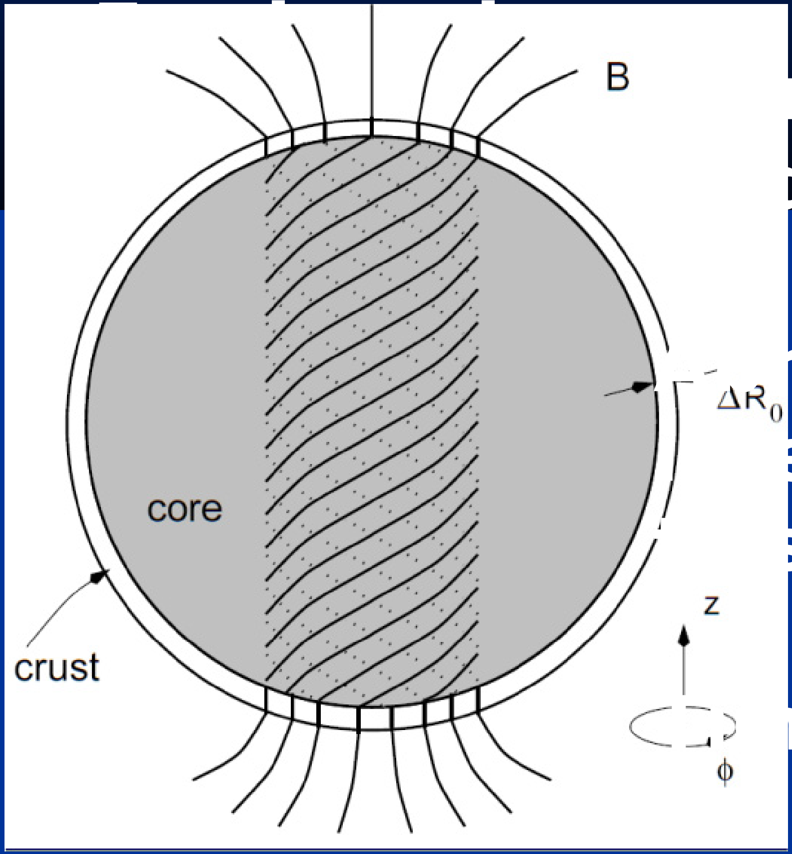
Two different models :

I. **Crust Model**

II. **Magnetosphere Model**

Crust Model

Sudden Crust Brittle Fracture, similar to



rong magnetic fields
duce stress on the crust.

rupt untwisting of the
erior magnetic field leads
sudden crust fracture

nescale ~ Shear Alfven wa
escale ~ 0.2 second

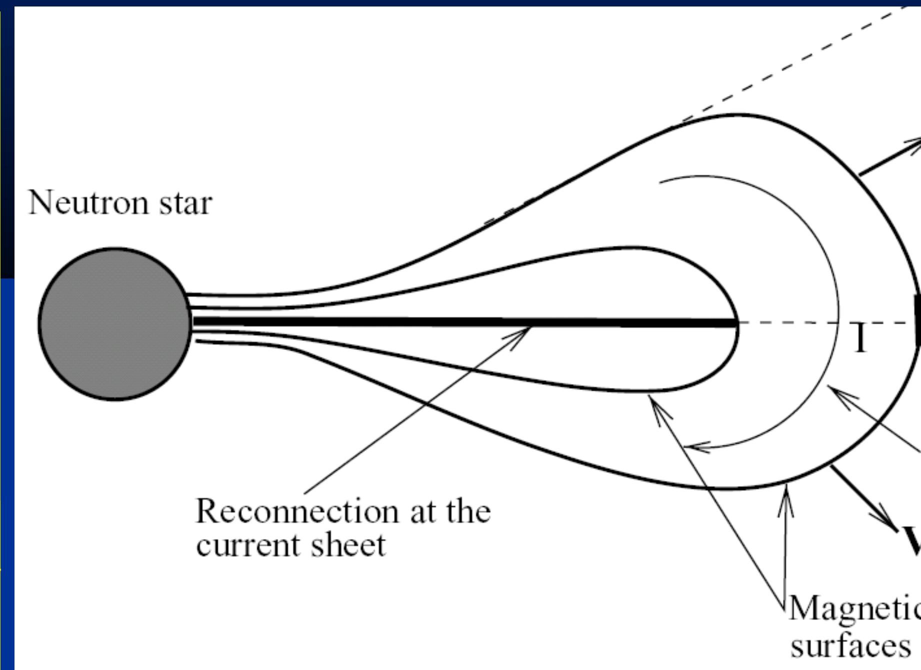
Crust Model **Thompson & Duncan (2000)**

Magnetosphere Model

Note: Sudden magnetosphere rearrangement due to gradual changes occur at the surface. NOT under crust guakes !

Alfven crossing timescale $\sim 30\,\mu s \sim R/V_A \sim R/c$

Given the ~ ms rise time of giant flares, this model seems to be more consistent with observations.



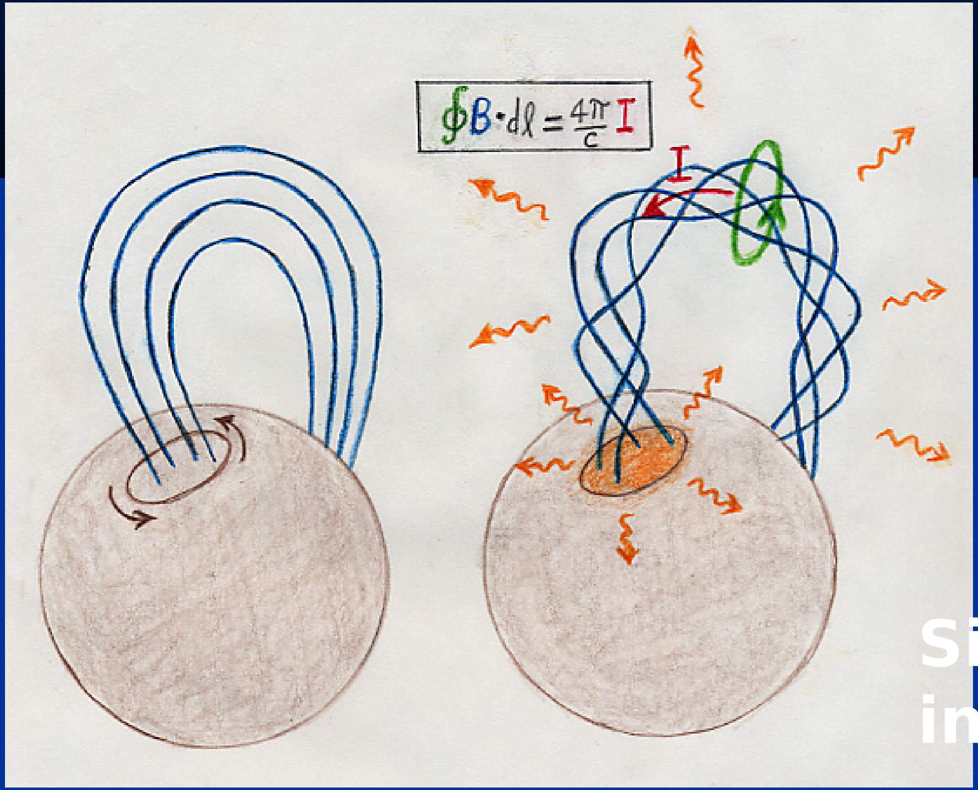
Lyutikov, 2006, MNRAS

However, no quantitative constraint has been placed on the relativistic reconnection rate based on real observations.

Part II

Flux Rope Eruption Model

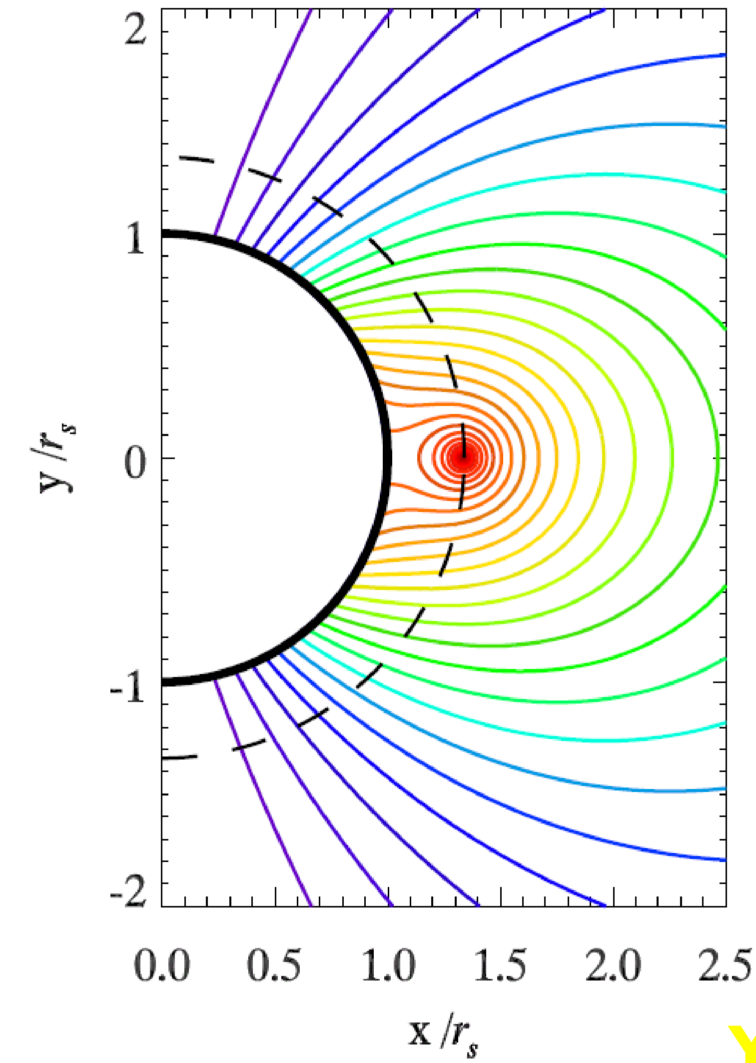
Cartoon for Giant Flares (Flux Rope Model)



Crust motion leads to the formation of helically twisted flux ropes

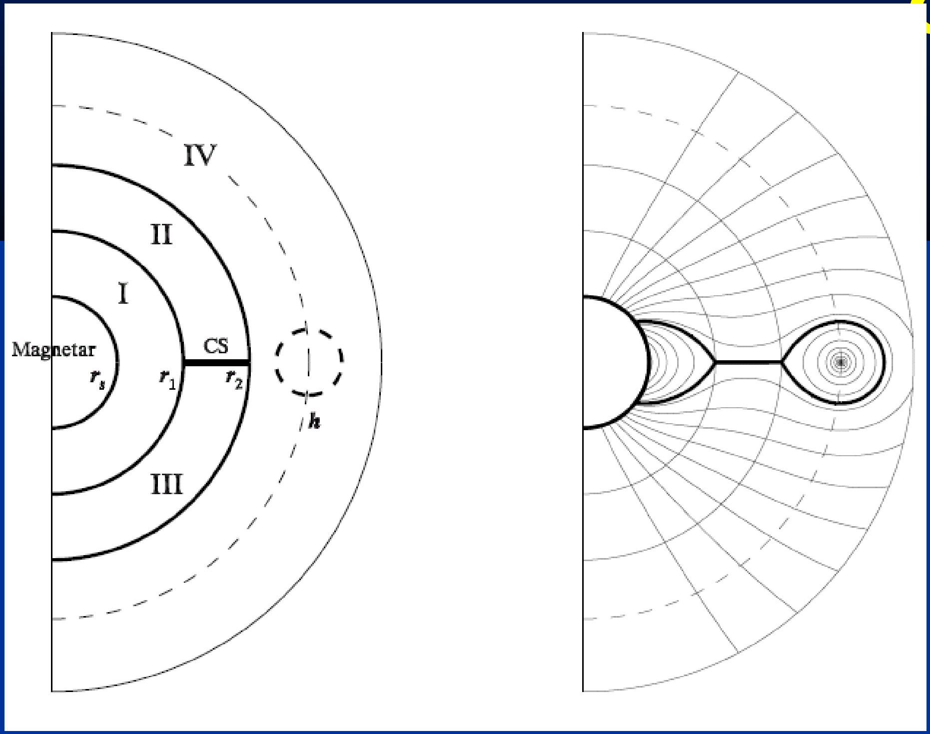
Similar to prominences in the solar corona.

Views in another Perspective



Yu, 2012, ApJ

Little Complication: Current Sheet



Central Object : Neutron Star

Electric current inside flux rope : I

Surface Magnetic Field : σ

Major Radius : h

Minor Radius : r_0

Current sheet : r_1 , r_2

Yu & Huang, 2013, ApJ Letter

lux Rope : Local Twist

f. Beloborodov (2009) Global twist

cf. Contopoulos, Kazanas, Fendt (19

Current Sheet beyond Light Cylin

Inhomogeneous Grad-Shafranov (GS) Eqn

Flux function $\Psi(r,\theta)$

$$\rho_e \mathbf{E} + \frac{1}{c}\mathbf{j} \times \mathbf{B} = 0$$

$$\frac{\partial^2 \Psi}{\partial r^2} + \frac{\sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial\Psi}{\partial\theta}\right) = -(r\sin\theta)\frac{4\pi}{c}J_\phi$$

**Inhomogeneous term :
contribution from currents
in the helically twisted flux rope**

$$J_\phi = \frac{I}{h}\,\delta(\cos\theta)\delta(r-h)$$

We numerically solve this GS equation.

Equilibrium Constraints

Force Equilibrium Condition :

Total Force = 0
(on the flux rope)

Flux Frozen Condition :

$$\Psi\left(h - r_0, \frac{\pi}{2}\right) = \text{cosnt}$$

h : major radius of the flux rope
r_0 : minor radius of the flux rope

Catastrophic Transition

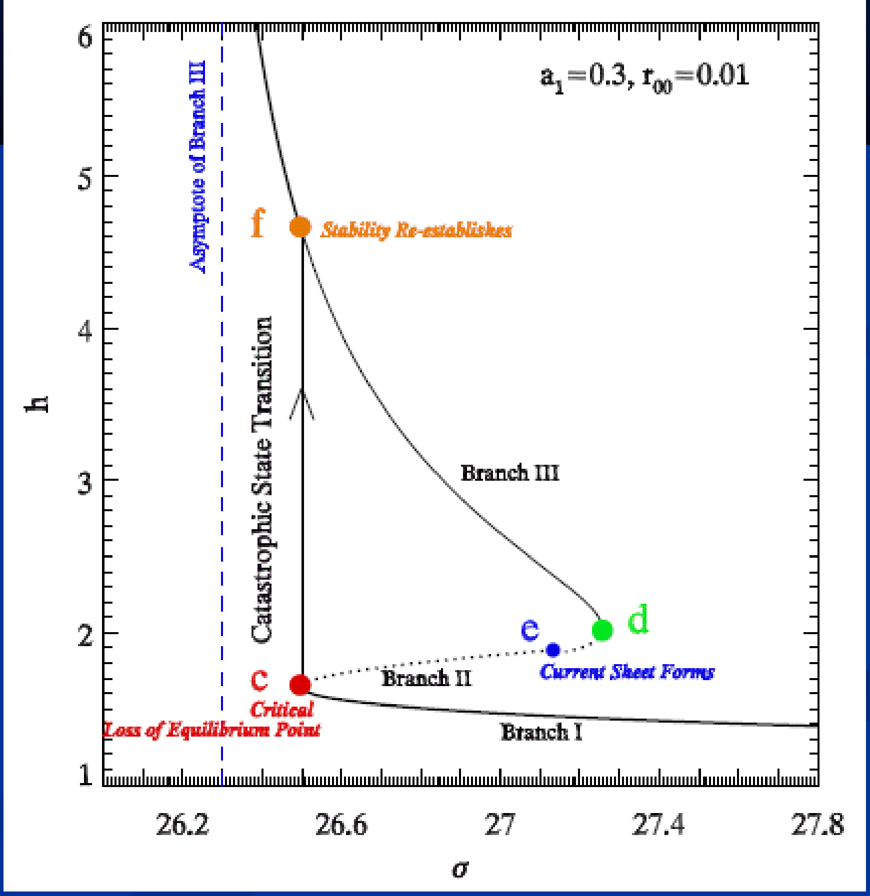
Huang & Yu, 2014a, ApJ
Huang & Yu, 2014b, ApJ

Catastrophic behaviors naturally explain a puzzle associated with magnetospheric model：

gradual variations (quasi-static timescale)

sudden energy release (dynamical timescales)

Three equilibrium branches appear alternatively：
stable, unstable, and stable



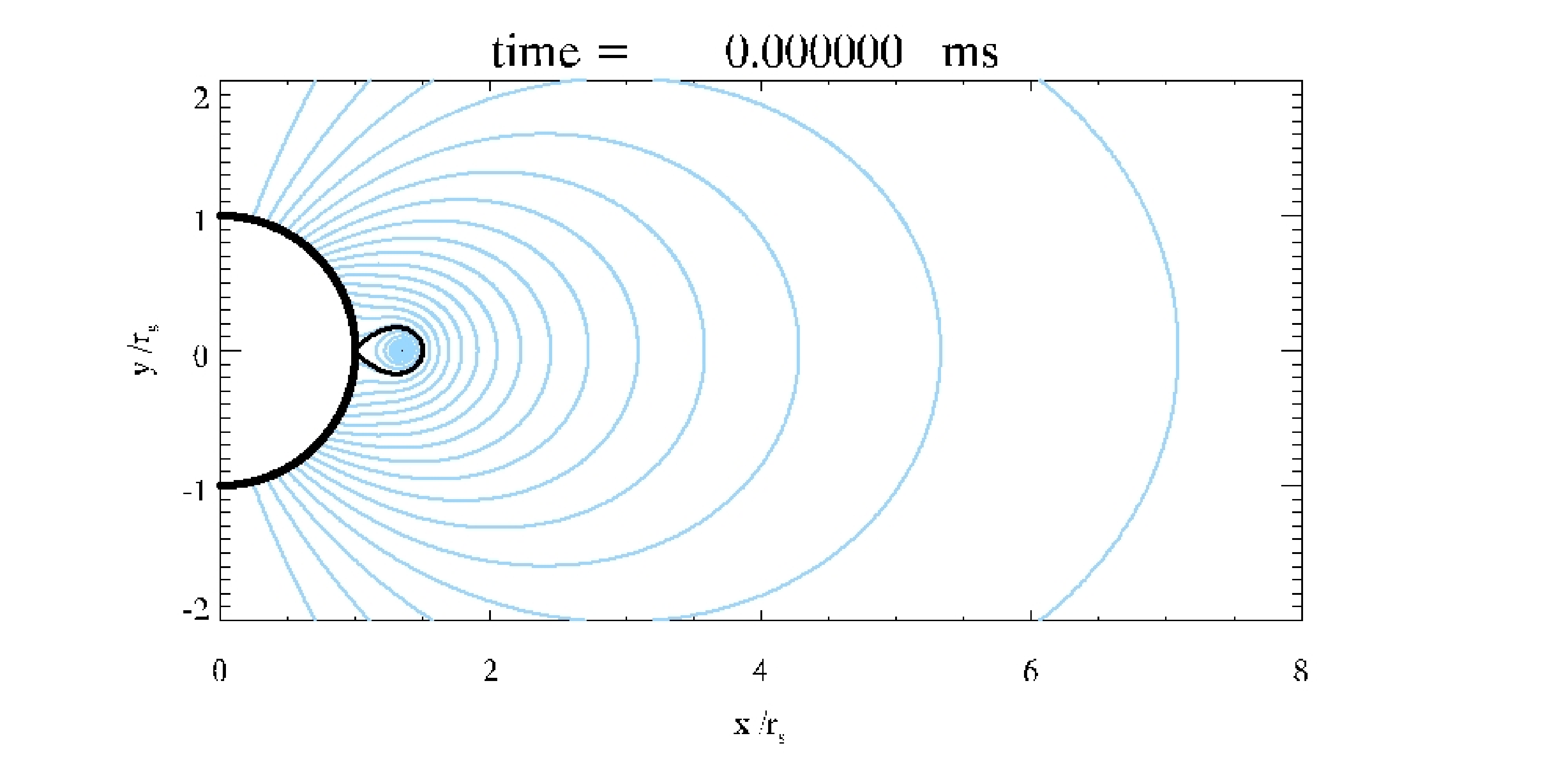
cf. S curves in accretion disc in CV

Part III

However …

- Take energy dissipation, i.e., magnetic reconnection into account !
- We need a time-dependent model !

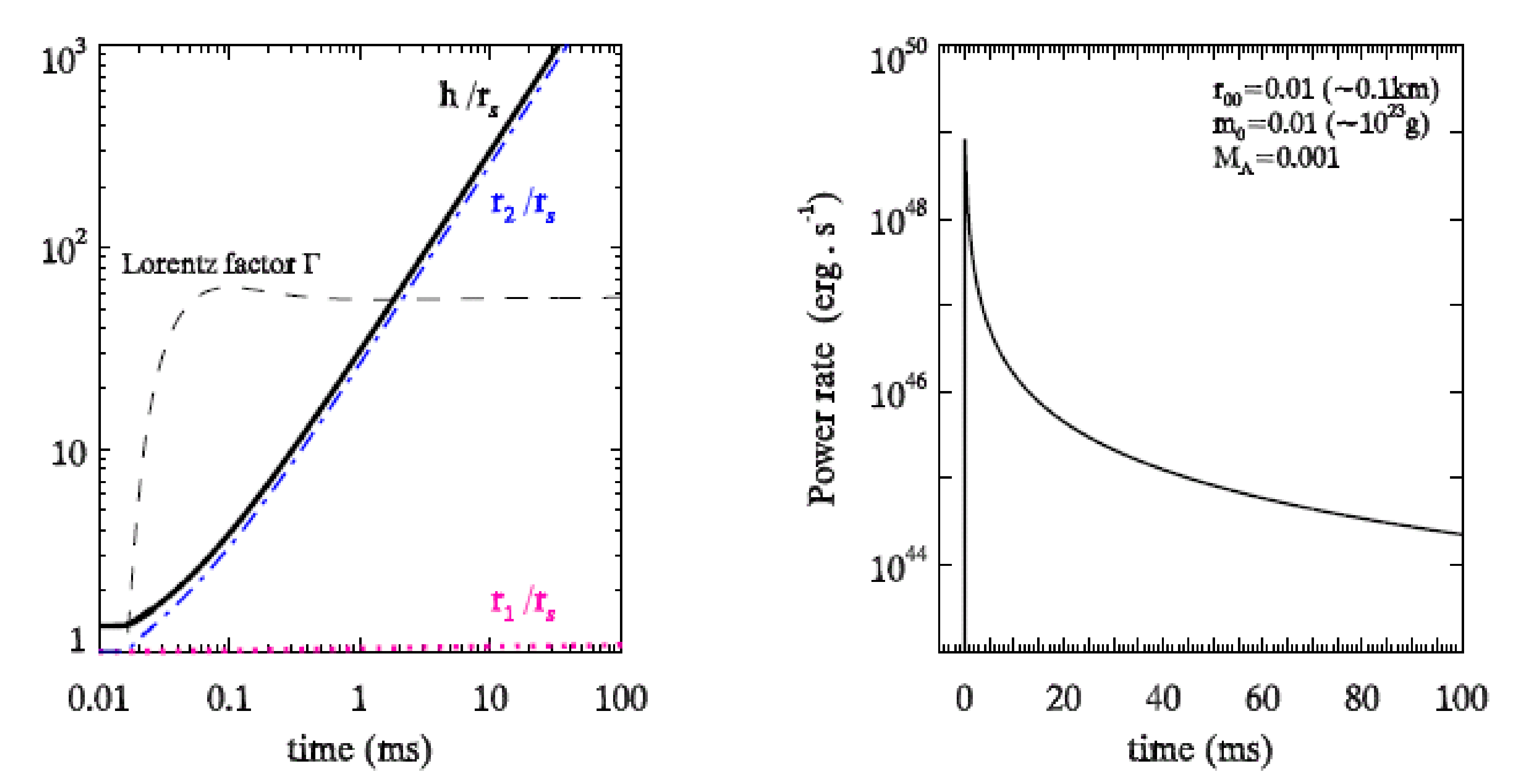
Time-Dependent Relativistic Models



Key parameter : $M_A = |v_\theta / v_a|$

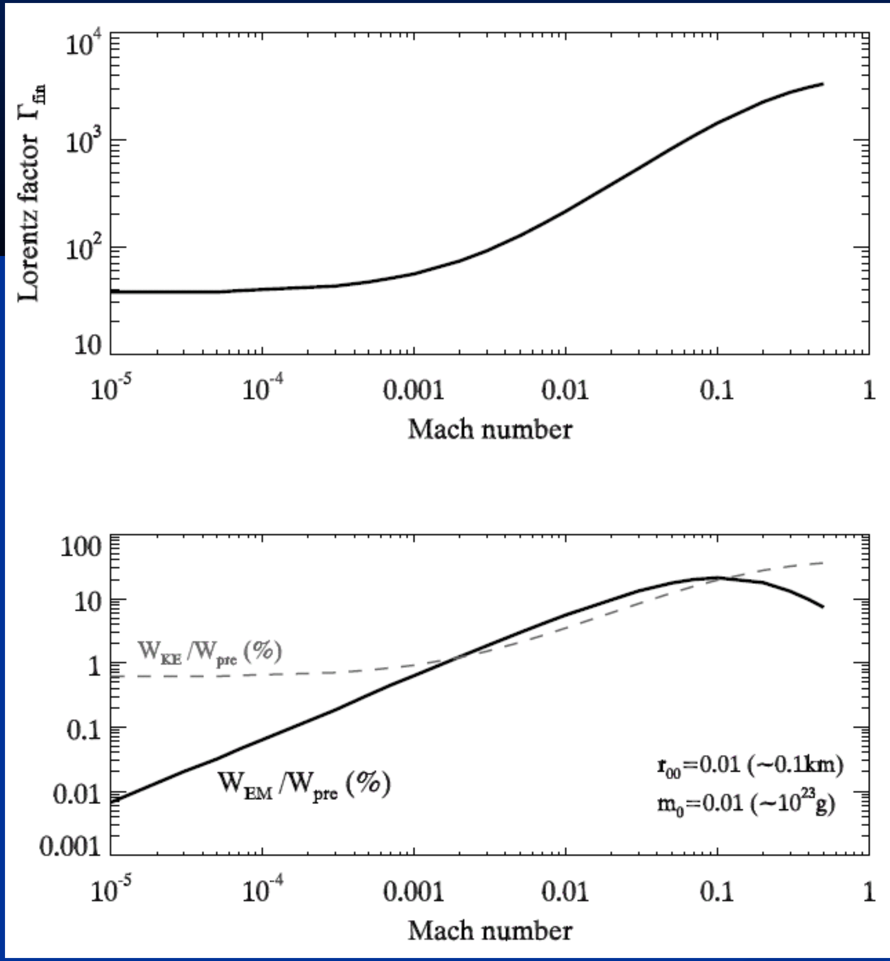
Yu & Huang, In prep.

Some Results



Yu & Huang, In prep.

Effects of Reconnection



Reconnection Rate

Spin-down rate during Giant Flare

Yu & Huang, In prep.

Conclusion

- We developed a self-consistent model which can constrain the relativistic reconnection according to the actual observations about magnetars.
- Reconnection may not be that rapid, Mach number ~ 0.001 is already enough to explain the observations.
- Spin-down behavior is consistent with magetar’s observations
- Important implication for solar CMEs, such as flareless CMEs

Thank you !