3D Force-Free Neutron Star Magnetospheres

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1. Introduction

What is a magnetar?

Magnetars

A class of NS with

- ★ Extreme magnetic fields $B \geq 10^{14} G$
- ★ Slow rotation $P \sim 1 - 10 s$
- ★ Young age

- ➔ Rapid spin-down due to magnetic braking
- ➔ Dissipation of magnetic energy into radiation
- ➔ Transient X-ray activity

2. Motivation

Why is it important to model Magnetar magnetospheres?

Observations

X-rays

- Short duration bursts
- Long duration outbursts
- Highly energetic flares
- Extended decays
- Pulsed emission

Origin of observational phenomenology

Presence of strong twisted magnetosphere linked to interior evolution

Critical point where the twist becomes unsustainable

Release of magnetic energy that feeds the X-ray activity

3.
Physical framework

How do we describe the problem?

Force-Free Field

Assumptions

1. Gravity, inertia and plasma pressure are much smaller than E/M forces
2. Rotationally induced electric fields are negligible due to slow rotation

Main equations

$$\mathbf{J} \times \mathbf{B} = 0$$

$$\Rightarrow \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\Rightarrow \mathbf{B} \cdot \nabla \alpha = 0$$

Grad-Rubin Method

- Decompose the problem in an elliptic part for **B** and a hyperbolic part for α
- Give boundary conditions at the surface
- Iterate until convergence

Decomposition

$$\mathbf{B}^{(n)} \cdot \nabla \alpha^{(n+1)} = 0$$

$$\nabla \times \mathbf{B}^{(n+1)} = \alpha^{(n+1)} \mathbf{B}^{(n)}$$

4. Results

What have we found?

A dipole with two hotspots

Surface boundary conditions:

$$B_R(\theta,\phi) = 2B_0\cos\theta$$

$$\alpha_{R^+}(\theta,\phi) = a_0 \exp\left[\frac{-(\theta-\theta_1)^2-(\phi-\phi_1)^2}{2\sigma^2}\right]$$

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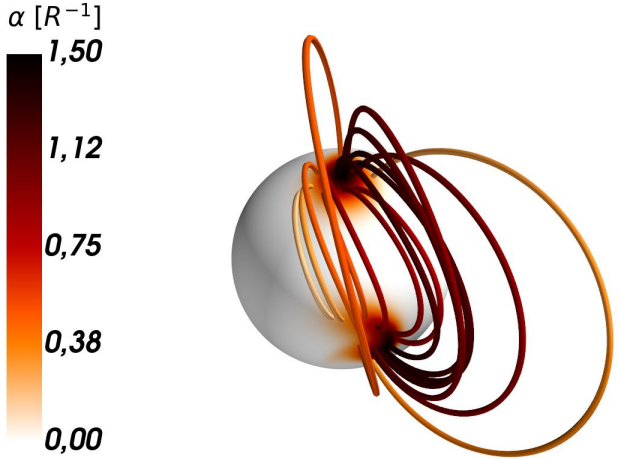

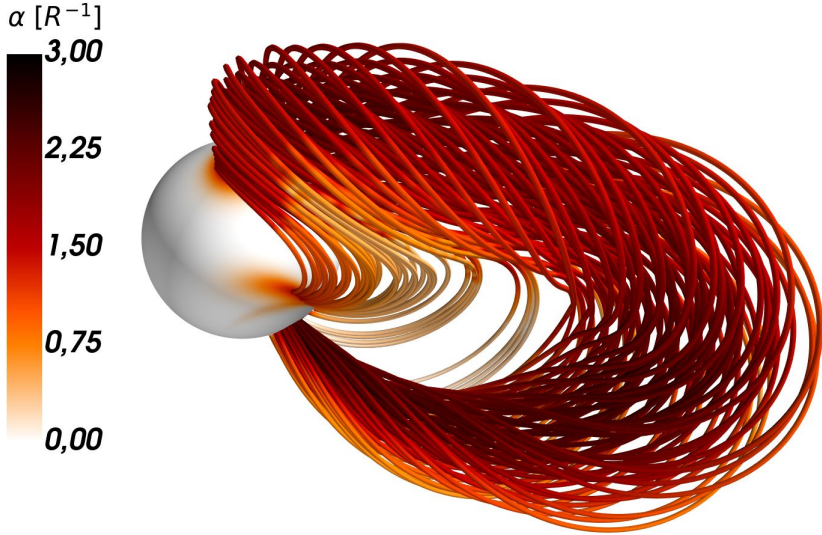

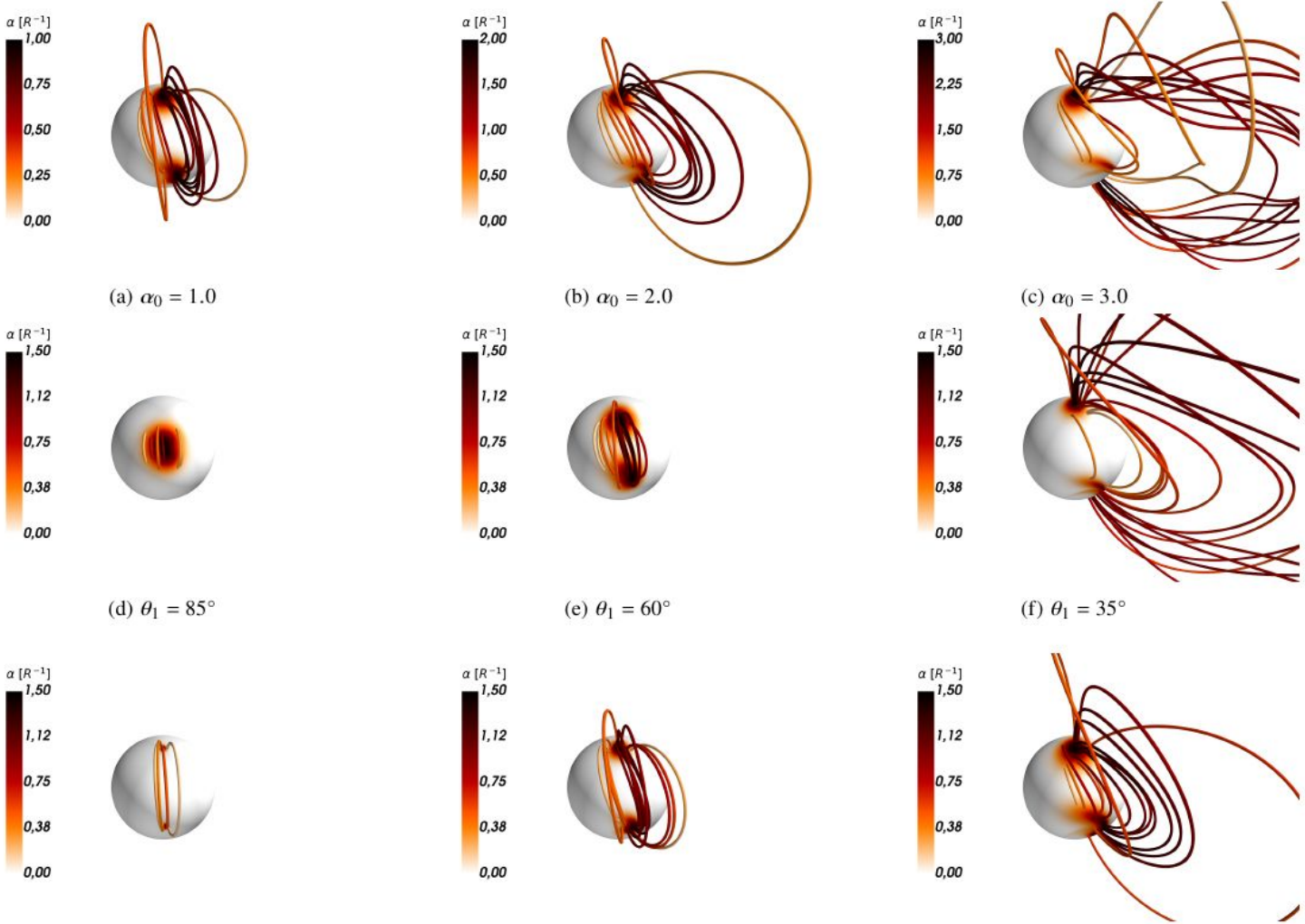

(a) $\alpha_0 = 1.0$ (b) $\alpha_0 = 2.0$ (c) $\alpha_0 = 3.0$

(d) $\theta_1 = 85°$ (e) $\theta_1 = 60°$ (f) $\theta_1 = 35°$

(g) $\sigma = 0.05$ (h) $\sigma = 0.15$ (i) $\sigma = 0.25$

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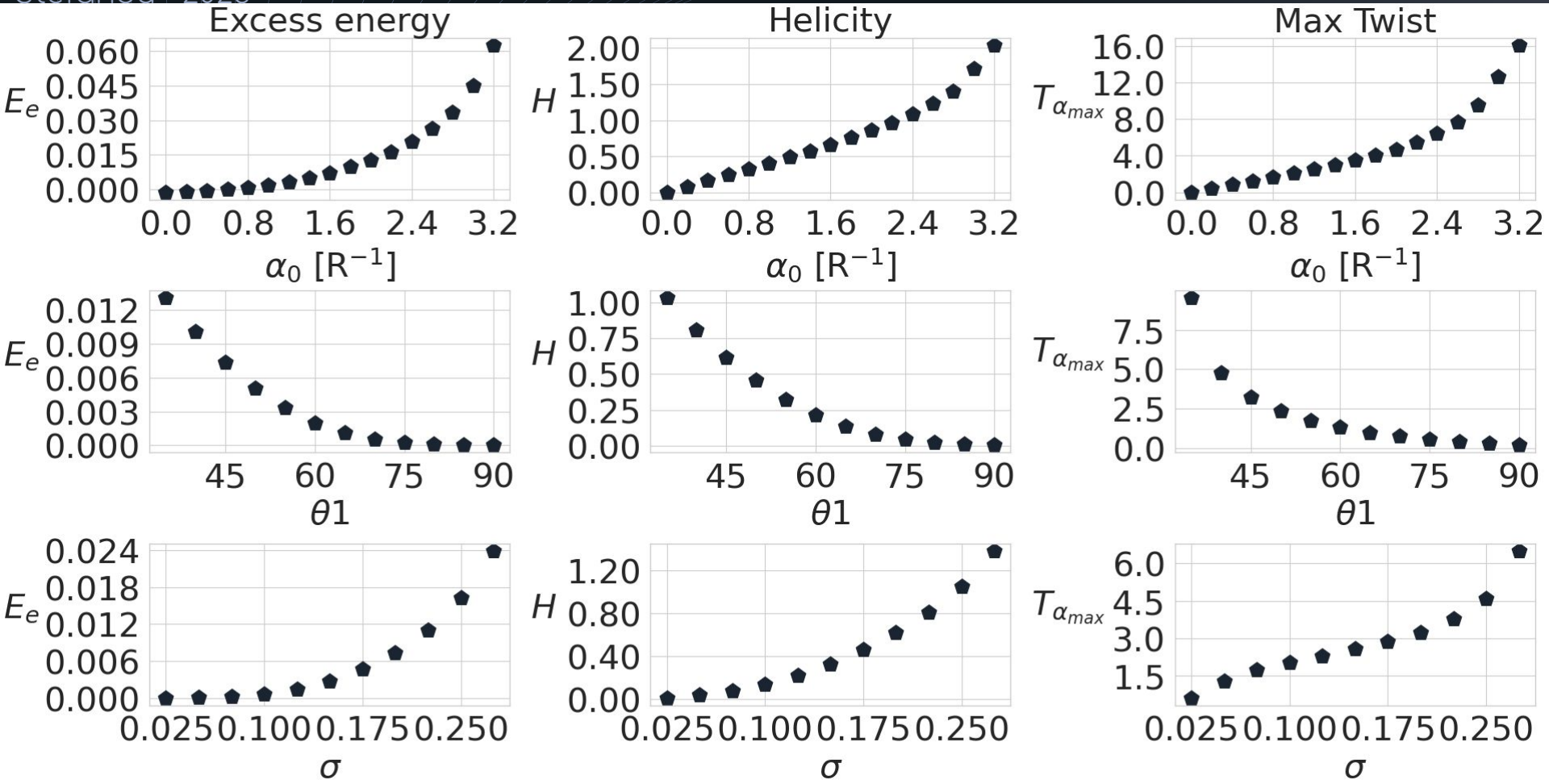
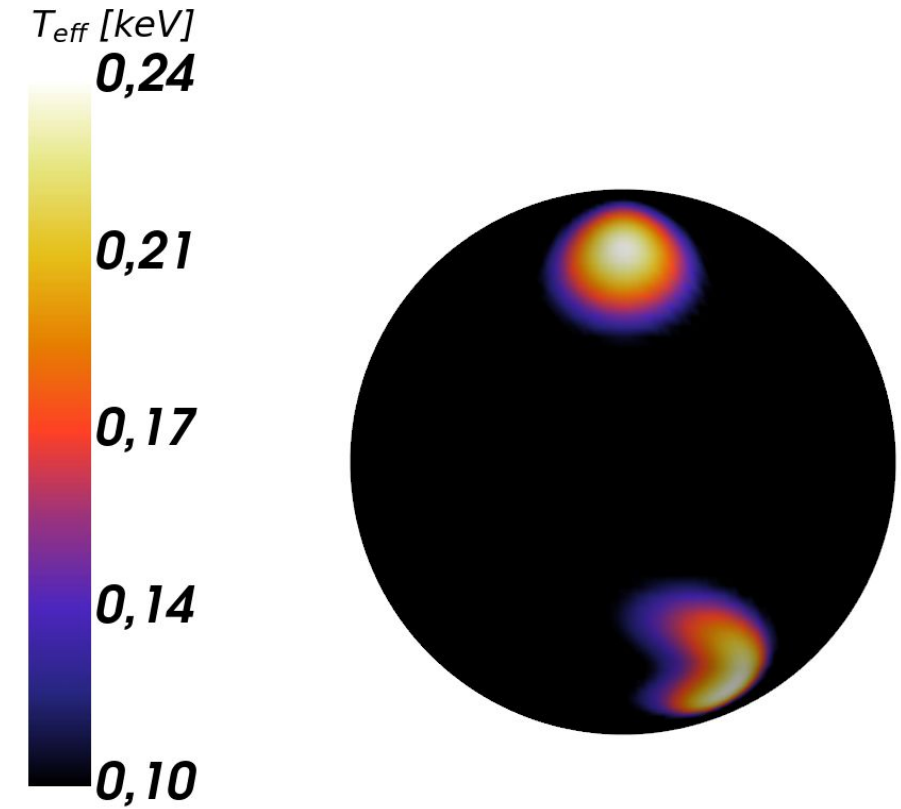

Excess energy
Helicity
Max Twist
E_e
H
$T_{\alpha_{max}}$
α_0 [R^{-1}]
$\theta 1$
σ



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5. Future Ideas

Where do we go from here?

- Multipole magnetic field
- Stability of solutions
- Emission spectrum
- Consider rotation
- Couple with interior evolution

Thank you!