Simulating the Twisted Life of Magnetars

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Exascale Thinking of Particle Energization Problems

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Magnetar: Phenomenology

Magnetars are rotating neutron stars with extra-strong magnetic field.

Spin period P and spindown $\dot{P}$ have been measured for most known magnetars. Most have $B > 10^{14}\,\mathrm{G}$. Spindown power usually much smaller than X-ray luminosity.

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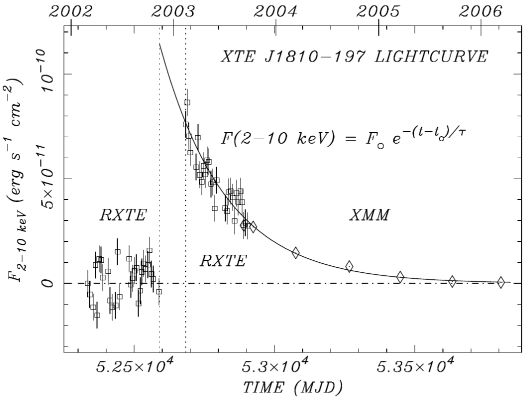
Bi-modal distribution in quiescent luminosity:

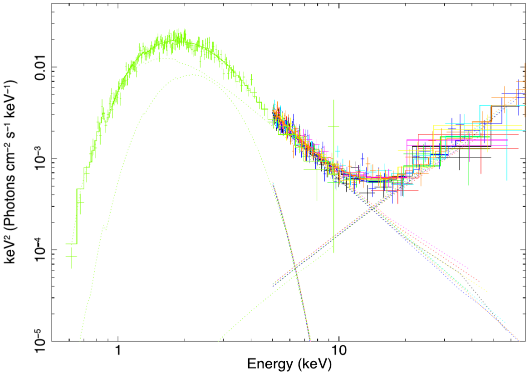
- Persistent magnetars: bright quiescent emission with rising spectrum at $> 10\,\mathrm{keV}$
- Transient magnetars: observed during outbursts, with sudden rise in luminosity and subsequent long decay

Light curve of transient magnetar XTE J1810-197 after outburst (Gotthelf & Halpern 2007)



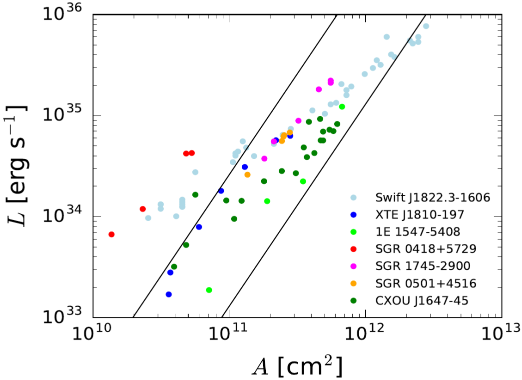
Magnetars: Examples

Persistent emission spectrum from 1E 2259+586 (Vogel et. al. 2014)



Shrinking Hotspot

The X-ray spectrum of a transient magnetar after outburst can often be fitted with a blackbody due to a hotspot on the star. 7 of the transient magnetars show a shrinking hotspot (Beloborodov & Li 2016)



Twisted Field Line Bundle

What happens when the crust is moved and Alfven wave is launched into the magnetosphere?

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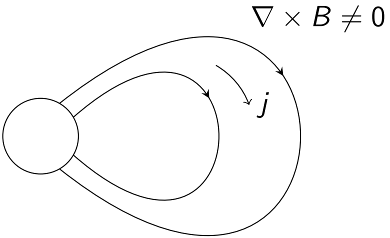
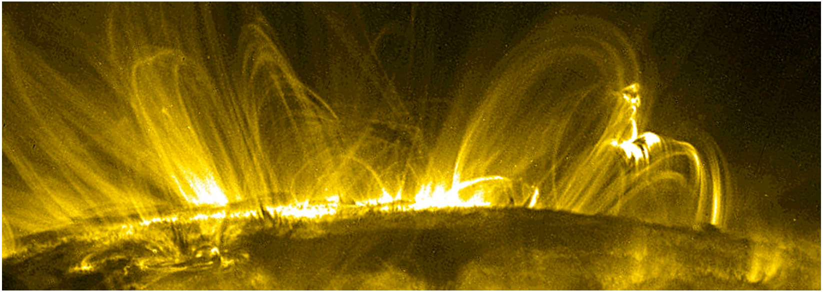
What happens when the crust is moved and Alfven wave is launched into the magnetosphere?

- Simplest case, an axisymmetric twist. Shearing motion on the star launches Alfven waves along the field lines
- Current will flow due to non-zero $\nabla \times B$
- Is the plasma extracted from the surface or from pair creation?



Magnetar Corona

The twisted field line bundle is similar to the solar corona



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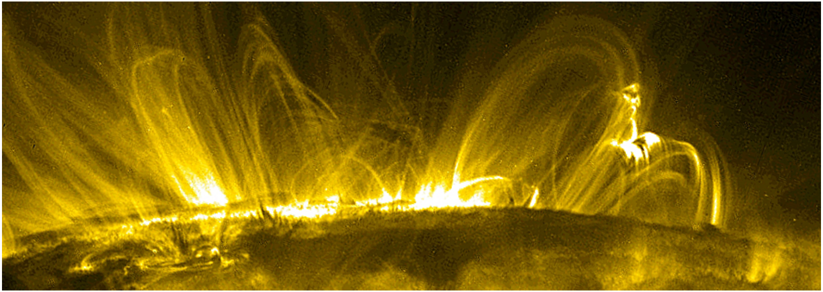

However the corona is charge-starved in the magnetar case. Pair creation is required to conduct the current.

Questions

Questions that can be answered by simulation:

- From first principles, what will actually happen if we launch a twist into the magnetosphere?

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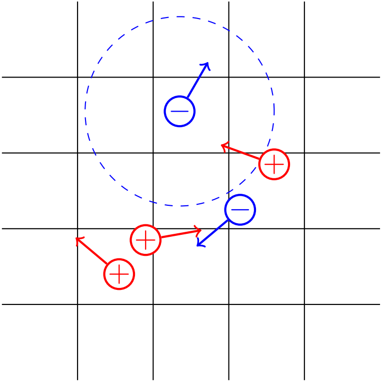
- From first principles, what will actually happen if we launch a twist into the magnetosphere?
- Is there a well-defined hotspot? Does it shrink with time?
- What sets dissipation rate, and timescale of the shrinking hotspot?
- Where are particles accelerated and where are pairs created to conduct the current? Are there localized “gaps” similar to those in pulsars?

Particle-in-Cell (PIC) Simulation

- Use meta-particles to approximate a distribution function
- Fields are discretized on a mesh grid
- Meta-particles move inside the grid cells
- Interpolating particle motion to the grid gives the discretized current
- Use the current to evolve the fields with Maxwell equations



Aperture

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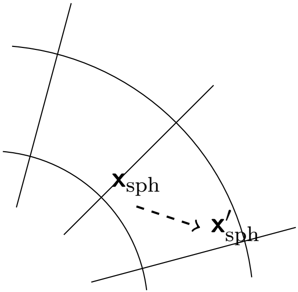
- High order finite difference schemes and particle form factors
- Esirkepov charge conserved current deposition
- Boris / Vay particle pusher
- Semi-implicit field update
- Curvilinear grid
- Pair creation / photon tracing
- First written in CUDA on Nvidia GPUs, then ported and parallelized on large CPU clusters

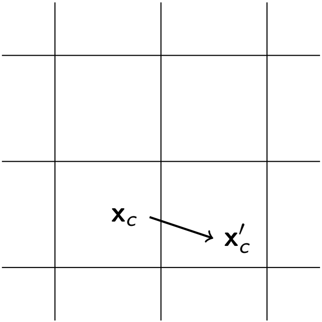
Aperture

Pushing particles in curvilinear coordinates



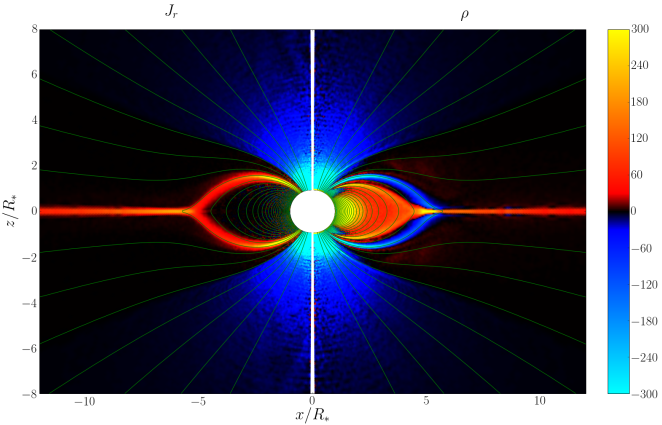
$\mathbf{x}_{\rm sph} \Rightarrow \mathbf{x}_c$

$\mathbf{x}'_c \Rightarrow \mathbf{x}'_{\rm sph}$



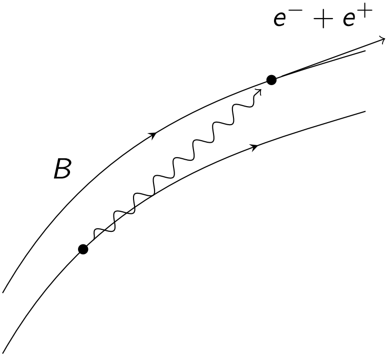
Pulsar Simulations

Pulsar simulation using Aperture (Chen & Beloborodov 2014)

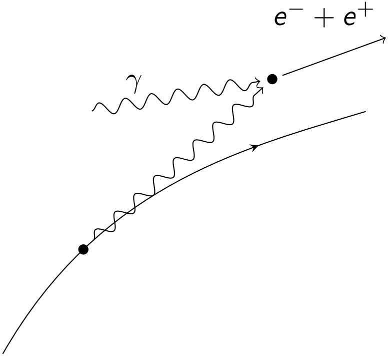


Model for Pair Production

Magnetic conversion

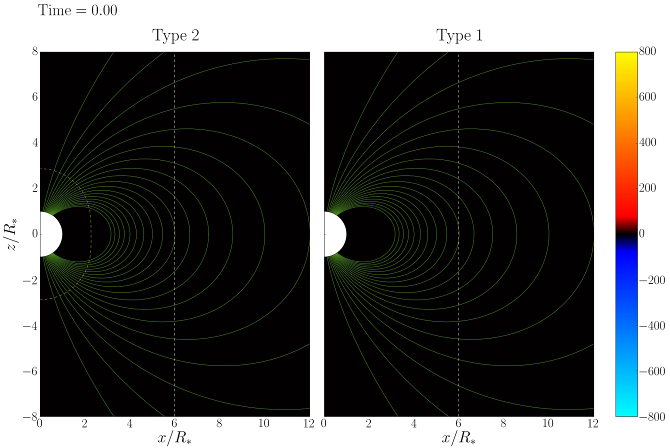


Photon collision



To emulate photon collision, we assign a random free path to photons and have them convert at the end of the free path

Two Types of Pulsars



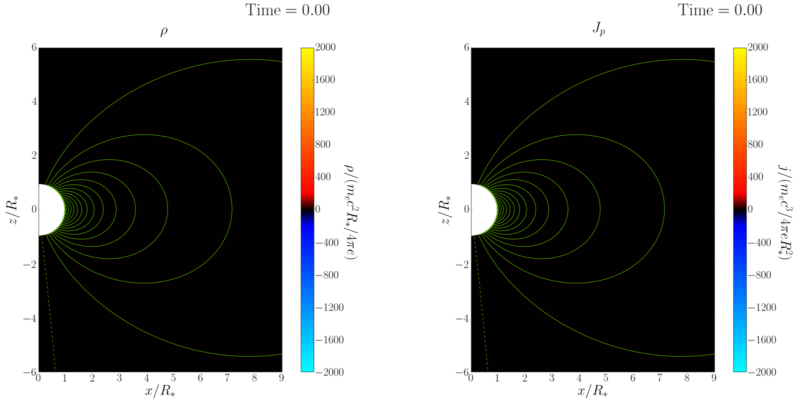
Numerical Challenges

- Pair creation can introduce vast load difference between nodes, slowing down the simulation by a factor of $\gtrsim 1000$.
- Excessive local charge density may also decrease plasma skin depth, certain regions may become unresolved
- In order to help with load balancing, we:
  - Annihilate pairs when local number of particles exceeds a given threshold
  - Dynamically assign duplicate nodes onto the same coordinate patch to help with particle calculation

Difference between Pulsars and Magnetars

- Pulsar activity is powered by its rotation, while magnetar activity is powered by the energy injected into the magnetic field
- Pulsar activity mainly happens on open field lines, whereas magnetar activity happens on closed field lines close to the star
- Different mechanisms for pair creation, which is directly reflected in numerical implementation
- Particles interact differently with background radiation

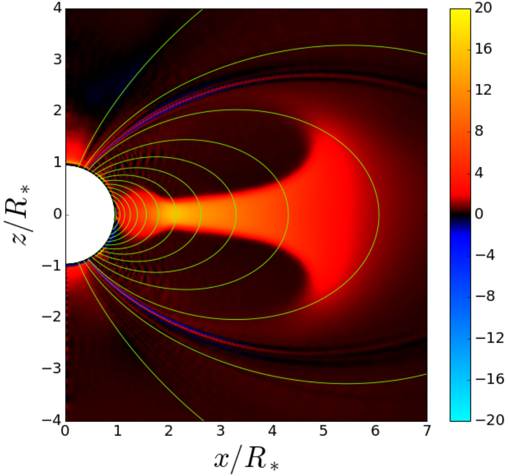
Magnetar Simulation



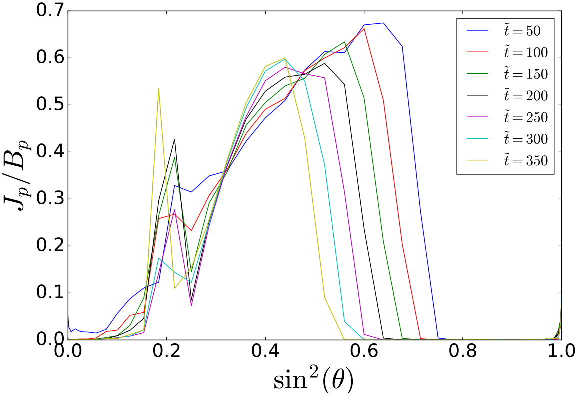
(Chen & Beloborodov 2016)

Equatorial Gap

Location of nonzero $\mathbf{E} \cdot \mathbf{B}$

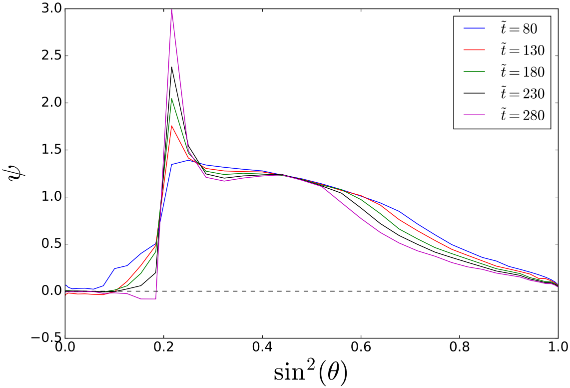


Expansion of Current Cavity



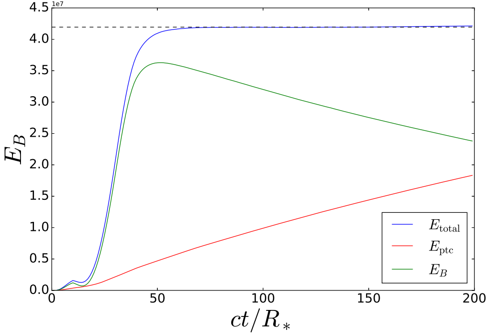
Twist Evolution

Twist angle ψ at different time slices



Energy Evolution

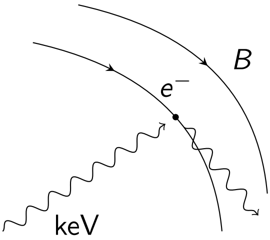
Energy is ultimately converted to particle kinetic energy and eventually advected into the star, since our simplified model is not radiative



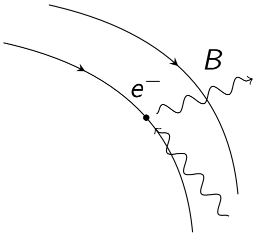
Overall voltage along the field lines is controlled by the threshold voltage

Resonant Scattering

In magnetar magnetosphere, resonant scattering of thermal X-ray photons is the main interaction between radiation and plasma



Lab frame



Electron frame

In the lab frame, resulting photon energy is upscattered by a factor of γ^2. Photon becomes capable of pair creation. Pair creation threshold depends on local B.

Resonant Drag

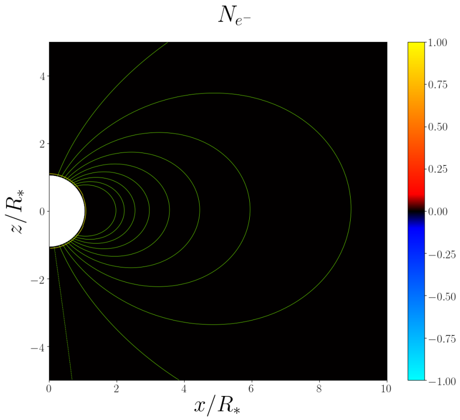
Resonant scattering also applies an effective drag force on particles

$$F(p) = \mathcal{D}(b, \Theta)\frac{1}{r^2}(p_* - p_\parallel)$$

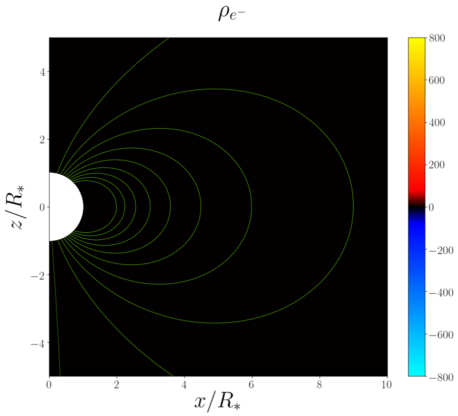
- The force will push particles toward a "preferred" velocity along magnetic field lines
- In a certain region, particles will be stopped by the radiation force around the equator

Resonant Drag

Resonant drag with test particles

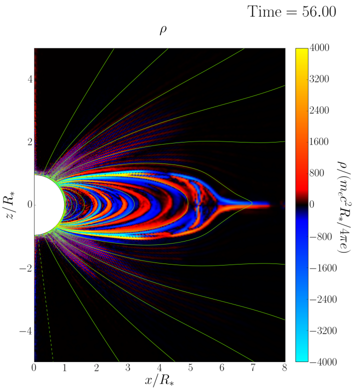


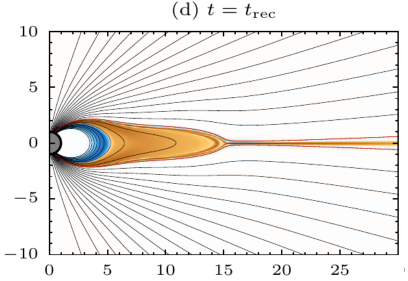
Simulation with Resonant Drag



Over-twisted Magnetosphere

When the twist angle becomes larger than some critical angle ψ_{crit}, the behavior of the *j*-bundle changes qualitatively. Untwist happens violently via reconnection.





(Parfrey et al. 2013)

Would be interesting to study the reconnection!

Summary

- PIC method has proved to be extremely useful in understanding the pulsar magnetosphere
- Same method can be applied to understand the twisted magnetosphere of magnetars. We see the self-consistent formation of a shrinking hotspot, and understand the first-principle evolution of the magnetosphere
- By adding radiative interactions, more detailed structure of the magnetosphere can be studied, potentially revealing the mechanism of hard X-ray emission