Resistivity and Dissipation in Pulsar Magnetospheres

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Overview

- Pulsars provide a unique laboratory to study plasma processes, dissipation, in high magnetic field environments

- 3 classes of pulsar solutions
  - Vacuum (no plasma in magnetosphere)
  - Force-free (abundant ideal plasma everywhere)
  - Resistive (solutions that combine plasma and accelerating fields)

- Applications of resistive solutions to intermittent pulsars, gamma ray pulsars
Non-ideal nature of Pulsar Magnetospheres

- We expect bulk of magnetosphere to have abundant ideal plasma due to pair cascade, but need accelerating electric fields to get high-energy radiation.

- Finite $E_\parallel$ can arise in “gap” regions due to variations in plasma supply and insufficient shorting of electric fields, or in reconnecting current sheets.

- $E_\parallel$ drives current and gives rise to resistivity, we specify $j_{\text{fluid}} = \sigma E_{\text{fluid}}$

Lab frame:

$$j = \frac{\rho c \vec{E} \times \vec{B} + \sqrt{\frac{B^2 + E_0^2}{B_0^2 + E_0^2}} \sigma E_0 (B_0 \vec{B} + E_0 \vec{E})}{B^2 + E_0^2}$$

$E_0$, $B_0$ magnitude of $E$, $B$ in fluid frame

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Pulsar electrodynamics

- We use a Finite Difference Time Domain Method to solve Maxwells equations with our resistive current closure

\[ \partial_t \vec{E} = c \vec{\nabla} \times \vec{B} - 4\pi \vec{j}, \]
\[ \partial_t \vec{B} = -c \vec{\nabla} \times \vec{E}, \]
\[ \vec{j} = \rho \vec{v} + \sigma E_{\text{fluid}} \]
\[ \vec{v} = c (\vec{E} \times \vec{B}) / (B^2 + E_0^2) \]
\[ E_{\text{fluid}} = \gamma (\vec{E} + \vec{v} \times \vec{B}) \]

- Problem: conducting neutron star with dipole field immersed in resistive plasma

- Method applicable to magnetically dominated systems in which plasma pressure and inertia are negligible

- Main application here to pulsar magnetospheres

- Potential applications to black hole magnetospheres, stellar and disk coronas, binaries, NS collapse
Resistive Pulsars

- Movie of field lines and current sheet for 60 degree inclined resistive pulsar solution with high but finite conductivity at:

  http://www.astro.princeton.edu/~jgli/rotator.mpeg
Force-free and high conductivity similar

\[
\sigma = 6 \Omega
\]

Li, Spitkovsky, Tchekhovskoy '12, ApJ 746, 60
Smooth transition to vacuum

\[ \sigma = 6 \Omega \]

\[ \sigma = 0.6 \Omega \]

\[ \sigma = 2 \Omega \]

\[ \sigma = 0.2 \Omega \]
Spin-down

- Magnetodipole radiation
- Conduction currents add to energy loss: \( W = IV \)
- Spin-down increases with conductivity
- What values of \( \sigma \) are observationally motivated?

\[
L_{ff} = \frac{\Omega^2 \mu^2}{c^3} \left(1 + \sin^2(\alpha)\right)
\]

\[
L_{\text{vac}} = \frac{2}{3} \frac{\Omega^2 \mu^2 \sin^2(\alpha)}{c^3}
\]

Li, Spitkovsky, Tchekhovskoy '12, ApJ 746, 60
How do real pulsars spin down? A look at Intermittent pulsars

- Switch between two distinct spin-down states
- Spin-down rates differ by factor of $\sim 1.5-2.5$
  - PSR B1931+24
  - PSR J1832+0029
  - PSR J1841-0500
- “on” radio-loud state and “off” radio-quiet state

Kramer et al. ’06
Why do Intermittent pulsars turn “on” and “off”?

- Switching suggests (Kramer et al. '06) some process is affecting plasma supply, giving us direct handle on plasma currents

- We construct quantitative model
  - “on” state is force-free with abundant plasma everywhere
  - In “off” state plasma supply on open field lines has been disrupted, but plasma remains trapped in closed zone
Current from toroidal advection of charged plasma in the closed zone leads to larger magnetic flux passing through the light cylinder and a larger fraction of open field lines (over vacuum).

Li, Spitkovsky, Tchekhovskoy '12, ApJL 746, 24
"on", force-free

\[ \alpha = 30 \]

\[ \alpha = 90 \]
Implications for Spin-down

\[ \frac{L_{\text{ff}}}{L_{\text{vac}}} = \frac{3}{2} \left( 1 + \sin^2(\alpha) \right) / \sin^2(\alpha) \geq 3 \] cannot explain intermittent pulsars

- Open field lines carry Poynting flux, so the larger fraction of open field lines in “off” state leads to spin-down factor of 2 higher than vacuum

Li, Spitkovsky, Tchekhovskoy '12, ApJL 746, 24
- Missing physics is toroidal advection of plasma in closed zone
- Uncertainties in “off” state spin-down ~ 10% of aligned force-free spin-down
- The spin-down ratio is broadly consistent with observations
- Intermittency may be related to nulling (also timing noise, rotating radio transients)
Gamma-ray pulsars

- Fermi LAT has discovered >100 Gamma-ray pulsars, many with double peaked light curves
- Main question: in what direction do gamma-ray emitting particles fly and beam?
- Reconnection heating in current sheets may be able to produce gamma ray emission (Bai & Spitkovsky '10, Petri '12, Petri & Kirk '05, Arka '12)
- MegaGauss B fields near light cylinder can produce comoving T ~ 100 MeV, boosted to GeV emission with modest γ ~ 10
Magnetic fields extrapolated to center of sheet, particles assumed to remember their trajectory from before entering sheet

Separatrix Layer Model (Bai & Spitkovsky '10), particles slipping down magnetic field and flying outwards radially in lab frame, emission from near sheet
Gamma-ray pulsars

- Reconnection microphysics may modify particle momenta

- Advantage of our resistive force-free method is that we can spatially resolve current sheet (unlike in ideal force-free)

- Beam along $E_{\parallel}$? Inwards streaming species won't give strong caustics and double-peaked light curves

- Should consider Lorentz force and relativistic dynamics?
Accelerating electric field circulating around sheet

Particles given strong kick by Lorentz force in current sheet, transferring angular momentum to particles?
Conclusions

- We have formulated a resistive force-free prescription to model plasma processes in pulsar magnetospheres

- More realistic physics opens new avenues of research:
  - We have produced quantitative models of intermittent pulsars
  - Resistivity naturally allows us to study high-energy emission from Gamma-ray pulsars
Open Questions

- What regulates plasma supply in pulsar magnetospheres?
- The importance of current sheet reconnection microphysics?
  - Localized reconnection in x-points may eject plasma relativistically in plasmoids
  - Particle In Cell simulation of current sheet structure would address momentum transfer to particles