Frontier Research Institute for Interdisciplinary Sciences
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Theoretical Astrophysics
Tohoku University

Relation between Blandford-Znajek Process and Penrose Process

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Discussion on:
the origins of the electromotive force and the Poynting flux in the Kerr BH magnetosphere with general conditions of BH spin and B field structure

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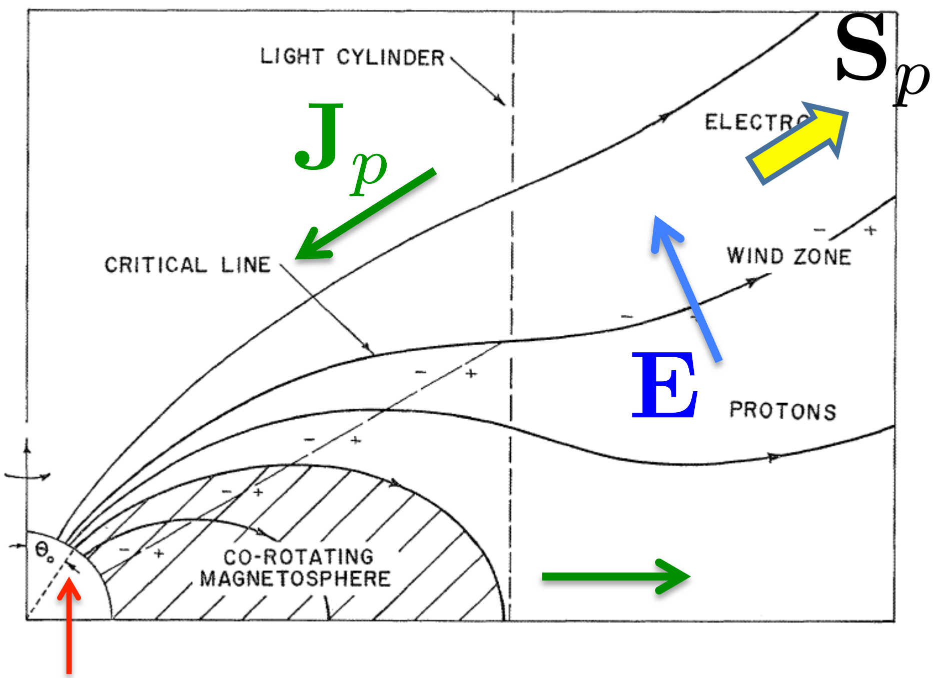
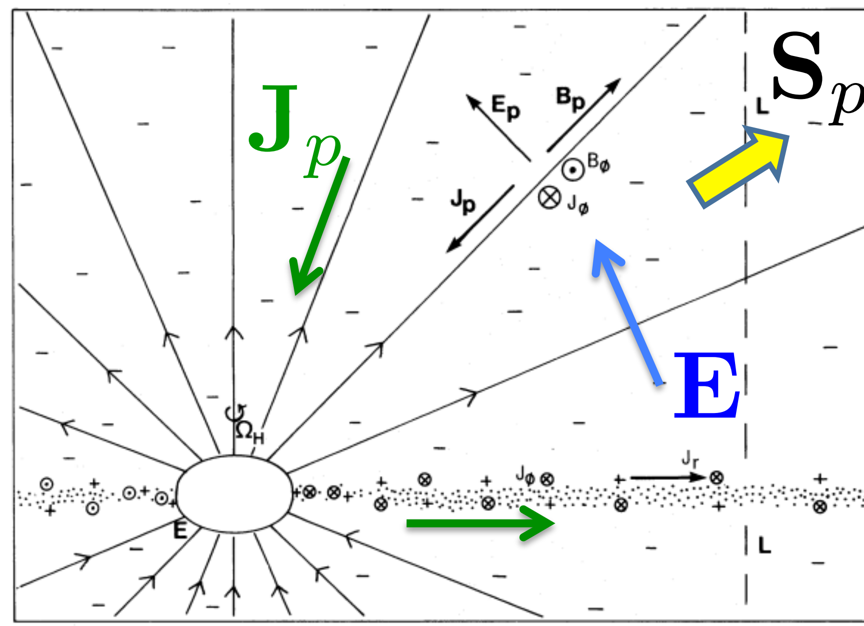
GJ pulsar-wind model & BZ process

(Goldreich & Julian 1969)

(Blandford & Znajek 1977)



Matter-dominated region



No matter-dominated region

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}$$

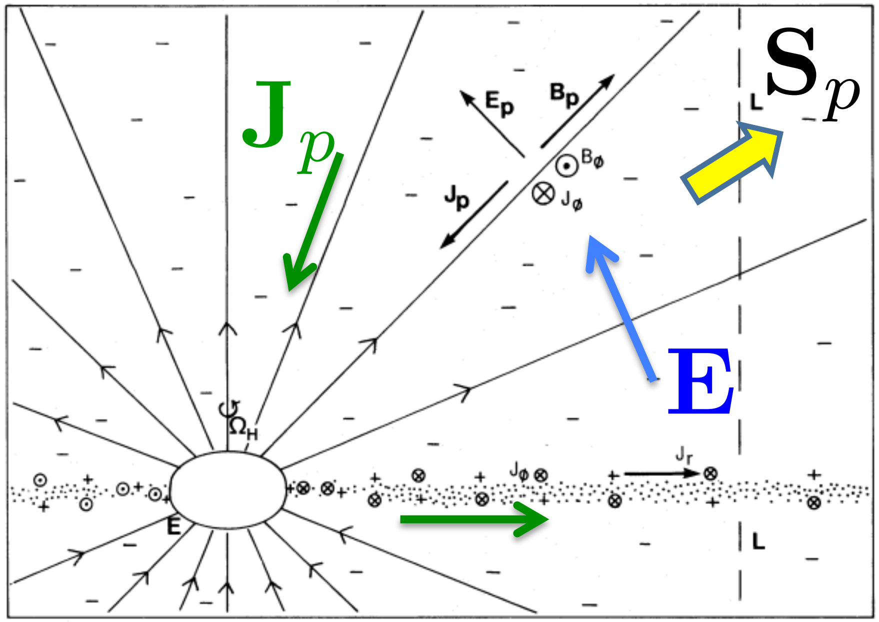
Origin of electromotive force?
What drives electric currents?

(see Komissarov 2009, JKPS)

BZ process

- The membrane paradigm (Thorne et al. 1986), but the horizon is causally disconnected (e.g. Punsly & Coroniti 1989)
- Analytical force-free/MHD solutions and studies (e.g. Camenzind, Okamoto, Takahashi, Beskin, Levinson)
- Numerical force-free/MHD solutions (e.g. Koide, Komissarov, Contopoulos, McKinney, Tchekhovskoy)

(Blandford & Znajek 1977)



No matter-dominated region

Origin of electromotive force?
What drives electric currents?

(see Komissarov 2009, JKPS)

3+1 Electrodynamics

$$E^\mu = F^{\mu\nu}\xi_\nu,\ H^\mu = -{}^*F^{\mu\nu}\xi_\nu$$ Fields in the coordinate basis

$$D^\mu = F^{\mu\nu}n_\nu,\ B^\mu = -{}^*F^{\mu\nu}n_\nu$$ Fields as measured by FIDO/ZAMOs

$$\nabla\cdot\boldsymbol{B} = 0, \quad \partial_t\boldsymbol{B} + \nabla\times\boldsymbol{E} = 0,$$

$$\nabla\cdot\boldsymbol{D} = 4\pi\rho, \quad -\partial_t\boldsymbol{D} + \nabla\times\boldsymbol{H} = 4\pi\boldsymbol{J},$$

$$\boldsymbol{E} = \alpha\boldsymbol{D} + \boldsymbol{\beta}\times\boldsymbol{B},$$

$$\boldsymbol{H} = \alpha\boldsymbol{B} - \boldsymbol{\beta}\times\boldsymbol{D},$$

Lapse Shift vector

Equations of electromagnetic energy & angular mom.

$$\partial_t\left[\frac{1}{8\pi}(\boldsymbol{E}\cdot\boldsymbol{D} + \boldsymbol{B}\cdot\boldsymbol{H})\right] + \nabla\cdot\left(\frac{1}{4\pi}\boldsymbol{E}\times\boldsymbol{H}\right) = -\boldsymbol{E}\cdot\boldsymbol{J},$$

Energy density Poynting flux

$$\partial_t\left[\frac{1}{4\pi}(\boldsymbol{D}\times\boldsymbol{B})\cdot\boldsymbol{m}\right] + \nabla\cdot\frac{1}{4\pi}\left[-(\boldsymbol{E}\cdot\boldsymbol{m})\boldsymbol{D} - (\boldsymbol{H}\cdot\boldsymbol{m})\boldsymbol{B} + \frac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{D} + \boldsymbol{B}\cdot\boldsymbol{H})\boldsymbol{m}\right] = -(\rho\boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B})\cdot\boldsymbol{m},$$

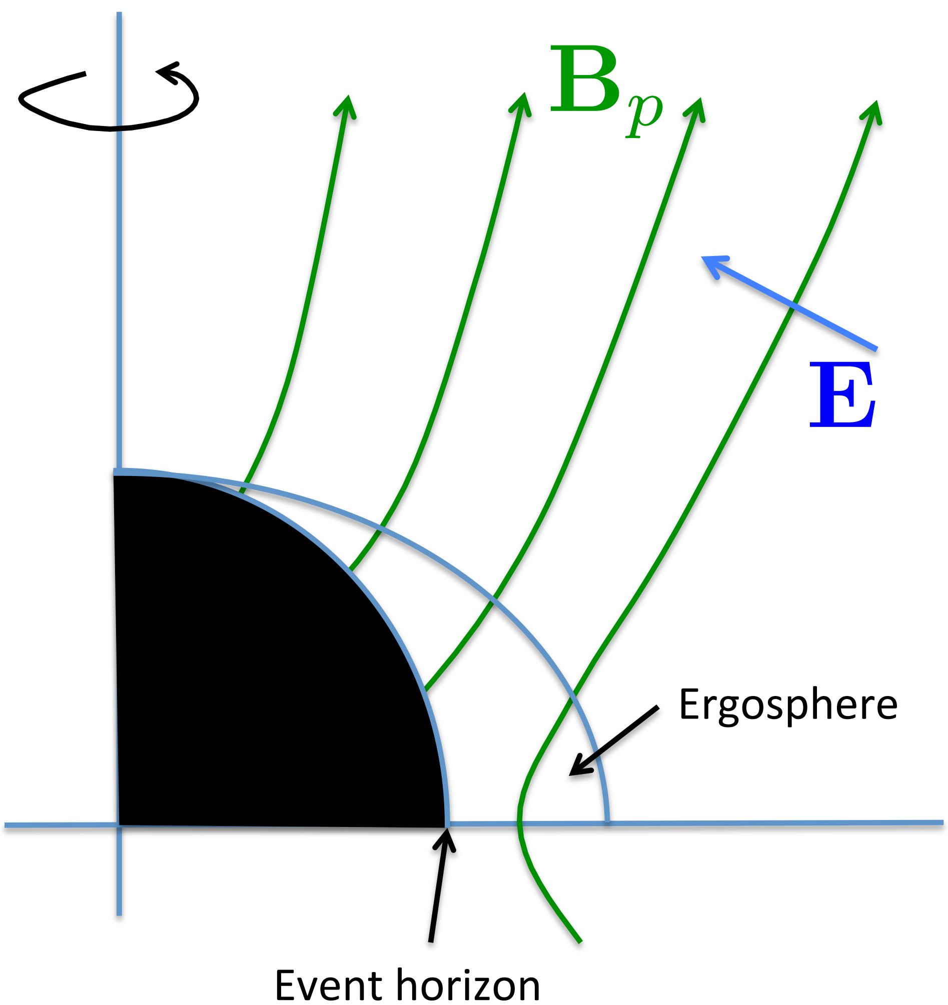
$$\boldsymbol{m} = \partial_\varphi.$$

Angular mom. density

Angular mom. flux

(Landau & Lifshitz 1975; Komissarov 2004)

General conditions of magnetosphere



- Kerr spacetime with arbitrary spin parameter (fixed)
- Steady & axisymmetric
- Poloidal B field (with arbitrary shape) threading the ergosphere
- Plasma with sufficient number density

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

(not assuming FF/MHD condition)

$$\Leftrightarrow \quad \mathbf{E} \cdot \mathbf{B} = 0$$

$$\boldsymbol{E} = \alpha \boldsymbol{D} + \boldsymbol{\beta} \times \boldsymbol{B},$$

Origin of Electromotive Force

$$\boldsymbol{E} = \alpha \boldsymbol{D} + \boldsymbol{\beta} \times \boldsymbol{B},$$

If $E=0$, $H_\phi=\alpha B_\phi=0$ (No ang. mom. or Poynting flux) along a field line,

$$\mathbf{D} = -\frac{1}{\alpha}\beta \times \mathbf{B}_p \quad \Rightarrow \quad D^2 > B^2 \text{ for } \alpha^2 < \beta^2$$

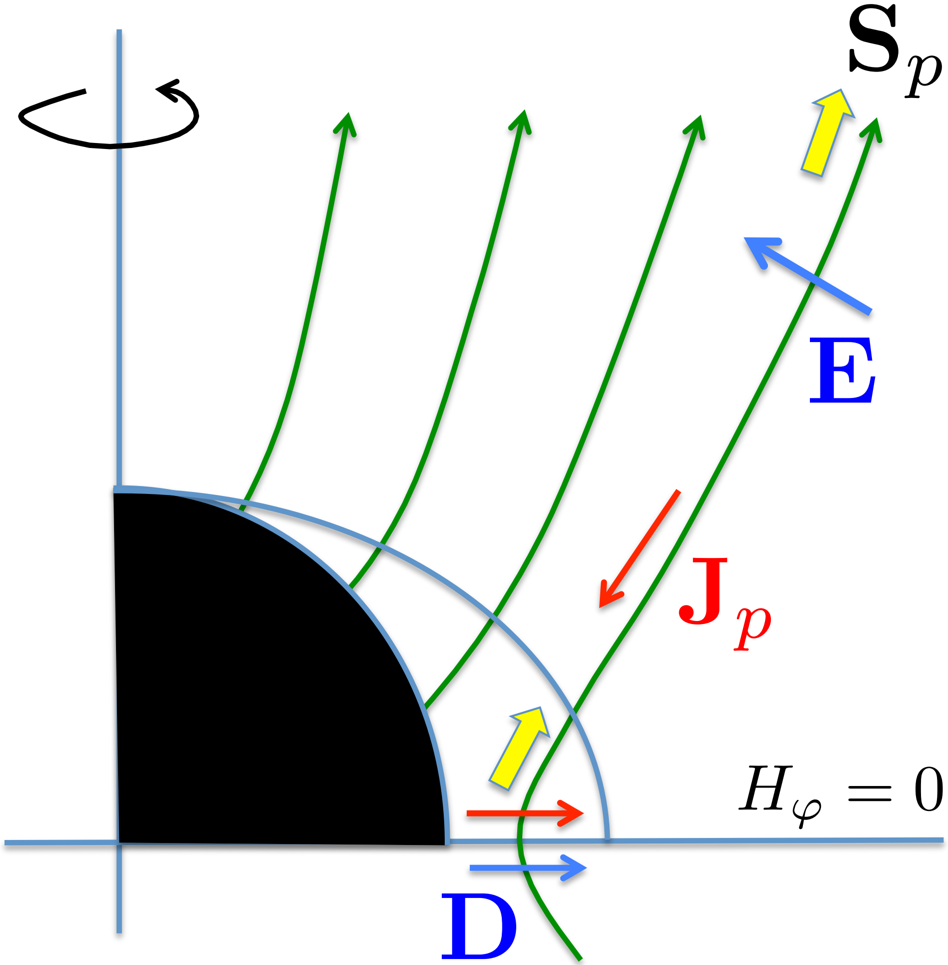
(in the ergosphere)

Then the force-free is violated, and the strong D field drives J_p across B_p ($H_\phi \neq 0$), weakening D ($E \neq 0$).

The origin of the electromotive force is ascribed to the ergosphere.

(KT & Takahara 2014, MNRAS; see also Komissarov 2004; 2009)

Field lines threading equatorial plane



- From the symmetry

$$H_\varphi = 0$$

on the equatorial plane

- $D^2 > B^2$ possible around there, creating AM flux (H_ϕ) & Poynting flux

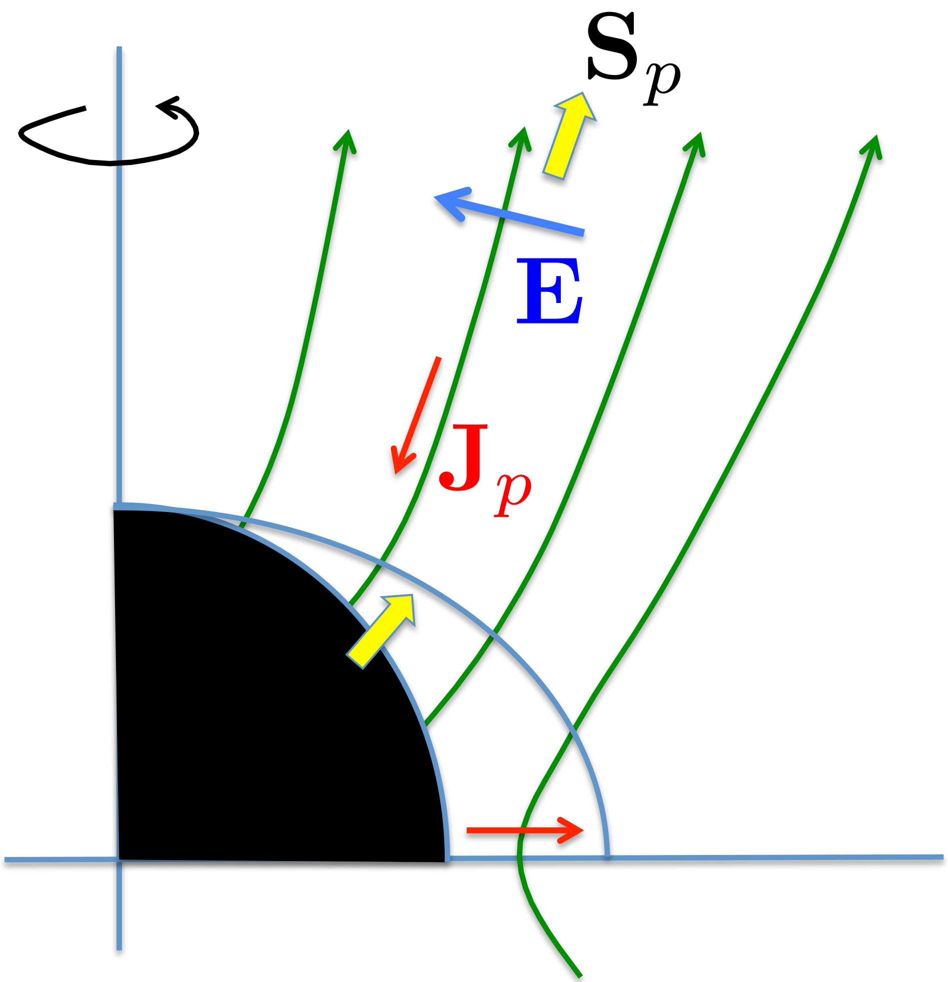
$$\nabla \cdot \mathbf{L}_p = -(\mathbf{J}_p \times \mathbf{B}_p) \cdot \mathbf{m}$$

$$\nabla \cdot \mathbf{S}_p = -\mathbf{E} \cdot \mathbf{J}_p$$

- For $D^2 \sim B^2$, particles are strongly accelerated in direction of $-\phi$, obtaining negative energies

(KT & Takahara 2014, MNRAS; KT & Takahara 2015 in prep.)

Field lines threading the horizon



- From the regularity condition

$$H_\varphi \neq 0, \quad D^2 < B^2$$

on the event horizon

- No particles with negative energies
- Negative EM energy e ? (Komissarov 2009; Koide & Baba 2014) But we found $e>0$ in the KS coordinates
- Different from Penrose process
- Then how is the steady S_p created ?

(KT & Takahara 2015 in prep.)

Process toward steady state

We try to understand this process with a toy model

Unpublished yet

Implications from the toy model

Unpublished yet

Summary

- Origin of E and J_p in pulsar wind is stellar rotation
- In the BZ process:
  - Origin of E is ascribed to the ergosphere
  - Around equatorial plane, J_p is driven by $D^2 > B^2$, creating $\varepsilon<0$ particles (appear same as Penrose process)
  - Around horizon, FF/MHD is satisfied in steady state (not appear same as Penrose process)
  - Our toy model implies that the boundary of force-free plasma and vacuum propagating inside has cross field current and displacement current flow, creating (or regulating) H_ϕ, S_p and L_p

(The presented analysis will be submitted soon. KT & Takahara in prep. 2015)