Title: Blandford-Znajek Mechanism: Event Horizon or Ergoregion?

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Abstract: There are good reasons to believe that relativistic jets of AGN are powered by rotating black holes via the Blandford-Znajek mechanism. Although the original mathematical solution, which demonstrated the possibility of such energy extraction, was found 37 years ago, its physical nature still remains a subject of debate.
I will give a brief review of some recent developments in this area with focus on the roles played by the EH and the Ergoregion in the Blandford-Znajek mechanism.

Blandford-Znajek Mechanism. Horizon or Ergoregion?

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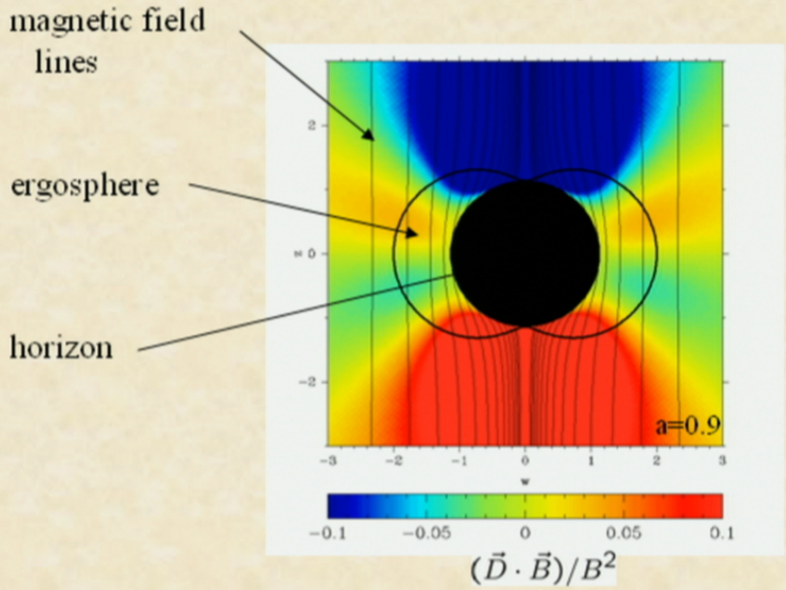
Historical overture

Wald's solution (Wald 1974)



Vacuum solution for a Kerr black hole in uniform magnetic field.

Gravitationally induced electric field with

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

Like around a rotating magnetized conductor.

Blandford & Znajek (1977) - copious pair production; force-free plasma-filled magnetospheres; BH energy extraction (Poynting flux). How to interpret this result? What drives the currents?

Macdonald & Thorne (1982), Thorne et al.(1986) – consider the event horizon as an inductor in the BZ mechanism, with surface charges, currents, torque, etc. – the membrane paradigm;

Punsly & Coroniti (1990) – The horizon is causally disconnected! The BZ solution is non-causal and unstable. Attractive alternative MHD mechanism - the magnetic field pushes plasma into orbits with negative mechanical "energy at infinity" in the ergoregion - the MHD Penrose process;

Komissarov (2001) – force-free numerical simulations show stability of the BZ-solution;

Komissarov (2004), Koide(2004), McKinney & Gammie(2004) – MHD simulations confirm the BZ-solution and disagree with the Punsly-Coroniti theory.

Back to square one !

Maxwell's electrodynamics

flat space-time, inertial frame

$$\nabla \cdot \mathbf{B} = 0,$$
$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0,$$
$$\nabla \cdot \mathbf{D} = \rho,$$
$$-\partial_t \mathbf{D} + \nabla \times \mathbf{H} = \mathbf{J}$$

+ constitutive laws relating E,B,D and H (properties of material)

In vacuum and plasma

$$\mathbf{B} = \mathbf{H}, \quad \mathbf{D} = \mathbf{E}\,.$$

3+1 black hole electrodynamics (Komissarov 2004)

$$\nabla \cdot \mathbf{B} = 0,$$
$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0,$$
$$\nabla \cdot \mathbf{D} = \rho,$$
$$-\partial_t \mathbf{D} + \nabla \times \mathbf{H} = \mathbf{J}\,.$$

constitutive laws

$$\mathbf{E} = \alpha \mathbf{D} + \beta \times \mathbf{B}\,,$$
$$\mathbf{H} = \alpha \mathbf{B} - \beta \times \mathbf{D}\,.$$

α - lapse function,
$\boldsymbol{\beta}$ - shift vector
(properties of space-time)

To the observer at rest in space (FIDO),
B is the magnetic and D is the electric field.

Space acts as an exotic electromagnetically active material.

*Axisymmetric steady-state poloidal magnetic field always induces non-vanishing electric field **D**.*

$$\left.\begin{array}{l}\partial_t\mathbf{B}+\nabla\times\mathbf{E}=0,\\ \mathbf{E}=\alpha\mathbf{D}+\beta\times\mathbf{B}\,,\end{array}\right\}\longrightarrow\nabla\times(\alpha\mathbf{D}+\beta\times\mathbf{B})=0$$

If **D** =0 then for a loop centered on the symmetry axis

$$\oint(\beta\times\mathbf{B})\cdot\mathbf{dl}=\oint\Omega_F dA_\phi=0 \quad\longrightarrow\quad A_\phi=A_\phi(\Omega_F).$$

(**A** – vector-potential, $\beta=\Omega_F\partial_\phi$ in the Boyer-Lindquist coordinates)

Along the symmetry axis A_ϕ is constant but Ω_F is not.

Hence $A_\phi=const$ and $\mathbf{B}=0.$

Wald's solution is one example of this general result.

Can this vacuum electric field be totally screened by a static distribution of electric charges ?   No!

Total screening means

$$\mathbf{D}\cdot\mathbf{B} = 0 \quad \text{and} \quad D^2 < B^2 .$$

Static means

$$\Omega = 0 \quad \text{and} \quad I_p = 0.$$

In such a static case

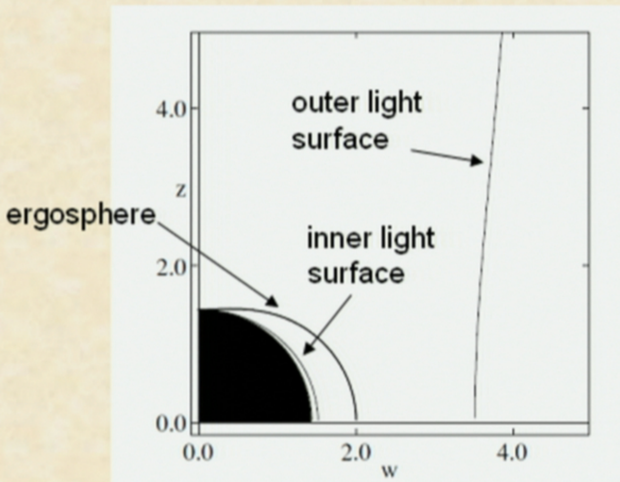
$$B^2 - D^2 = \frac{\alpha^2 - \beta^2}{\alpha^2} B^2 .$$ (Komissarov 2004).

However, inside the ergosphere $\alpha < |\beta|$ and hence $|D| > |B|$ - the electric field is not screened.

Rotation introduces two light surfaces with subluminal rotation in between of them and superluminal outside. Without poloidal current, we still have D>B in the superluminal regions:

$$(B^2 - D^2)\alpha^2 = B^2 f(\Omega, r, \theta) + (\Omega - \Omega_F)^2 \left(\frac{I_p}{2\pi}\right)^2 ,$$

with $f(\Omega, r, \theta) < 0$ in the superluminal regions (Komissarov 2009). This is why currents must flow in a force-free magnetosphere with screened electric field.



The inner light surface is always inside the ergosphere.

Is the Blandford-Znajek process related to the Penrose process?

(Komissarov 2009)

FIDO measures

$\hat{\mathcal{E}} = (D^2 + B^2)/2$ - energy density

$\hat{\mathbf{S}} = \mathbf{D} \times \mathbf{B}$ - energy flux density

(Local conservation)

Global conservation law:

$$\partial_t \mathcal{E} + \nabla \cdot \mathbf{S} = -(\mathbf{E} \cdot \mathbf{J})\,.$$

$\mathcal{E} = (\mathbf{E} \cdot \mathbf{D} + \mathbf{B} \cdot \mathbf{H})/\mathbf{2}$ - density of “energy at infinity”

$\mathbf{S} = \mathbf{E} \times \mathbf{H}$ - flux density of “energy at infinity”

Only at infinity $\mathcal{E} = \hat{\mathcal{E}}$ and $\mathbf{S} = \hat{\mathbf{S}}$!

Force-free steady-state axisymmetric magnetospheres. Energy counter-flow.

For the poloidal components of the electromagnetic fluxes

$$\mathbf{S}_p = \alpha^2 \frac{\Omega}{\Omega - \Omega_F} \hat{\mathbf{S}}_p$$

Ω, Ω_F - angular velocities of magnetic field and FIDO respectively

- When $0 < \Omega < \Omega_F$ a flow of energy towards the black hole implies a flow of "energy at infinity" away from the black hole!
- When $0 < \Omega < \Omega_{BH}$ this condition is satisfied near the EH;
- The $\Omega = \Omega_F$ surface separates inflow and outflow zones – inside of this surface $\hat{\mathbf{S}}_p$ points inwards and outside of it outwards.

This is the electromagnetic version of the Penrose process.

The EH passively accepts inflow of electromagnetic field (and particles), which coexists with outflow of "energy at infinity".

This flow separation surface can be located outside of the ergosphere.

Lasota et al. (2014) - describe the BZ mechanism as an electromagnetic Penrose process using fully covariant spacetime formulation.

Koide & Bada (2014) – further development of the energy counter flow notion; presenting the flux of energy at infinity at EH as

$$\mathbf{S} = \mathcal{E}\mathbf{v} \quad \text{with} \quad \mathcal{E} < 0$$

where the inward-pointing vector **v** is interpreted as the velocity of magnetic field lines.

Conclusion:

"In the 1990's, there was some controversy about whether the Blandford-Znajek process was actually theoretically viable, but that has been resolved and the process itself is now well understood."

(Teukolsky, 2014)