Exploring black hole engine

Yasufumi Kojima
Hiroshima Univ.

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Blandford-Znajek process as engine

Blandford-Znajek (1977)

A process to extract BH Rot. energy by EM fields

BZ Power

Kerr BH(Mass M, Spin a) $P_{BZ} \approx B^2 (a/M)^2 {r_H}^2 c$

\+ Magnetic field B $\approx 10^{45} erg/s (M_9)^2 (B_4)^2$

Comparison

$P_{sync} \approx B^2 (\beta\gamma)^2 \sigma_T c$

There have been so many works including MHD numerical simulations, ….But, there still remain problems.

'BZ' refers to a process in Mag. dominated case $(B^2 >> \rho c^2)$ in BH spacetime in this talk .

-->> Theoretical/observational puzzles will be solved in a decade.

Contents

- A brief look at SMBH in M87
- Primer of Blandford-Znajek process with caution
- Problem of EM structure near horizon
  - Origin of electromotive force -
- Poynting flux generation by falling of collisionless pairs

YK MNRAS,454(2015),3902 arXiv:1509.04793

- Remark

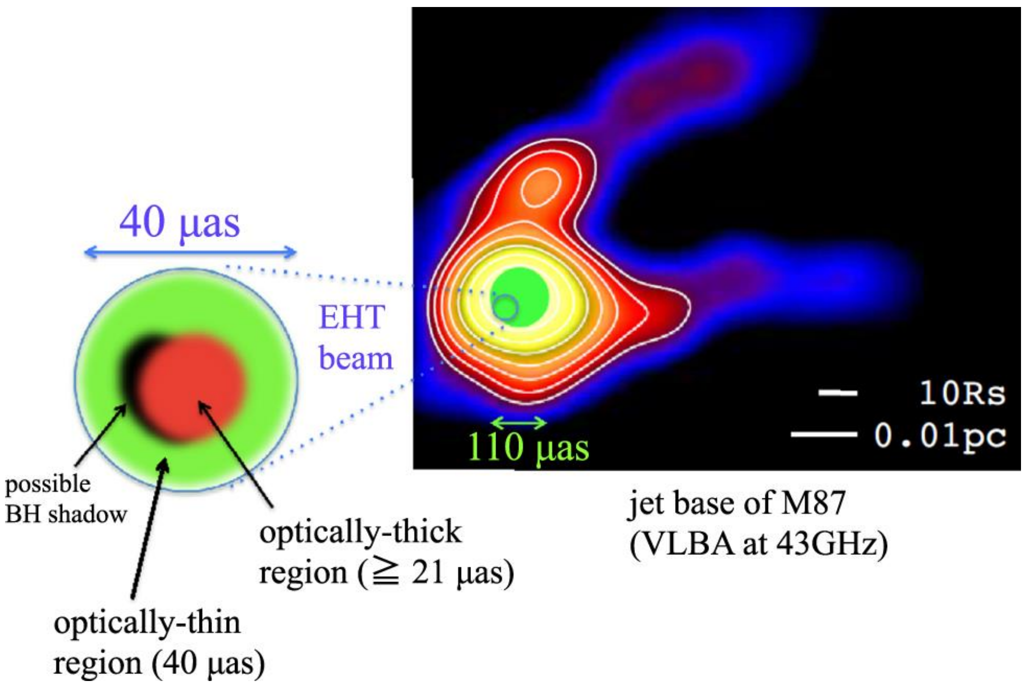
BH in a center of M87

A system of SMBH + Jets revealed within ~20 M

$$d = 16.4 Mpc (0.''1 = 8 pc)$$

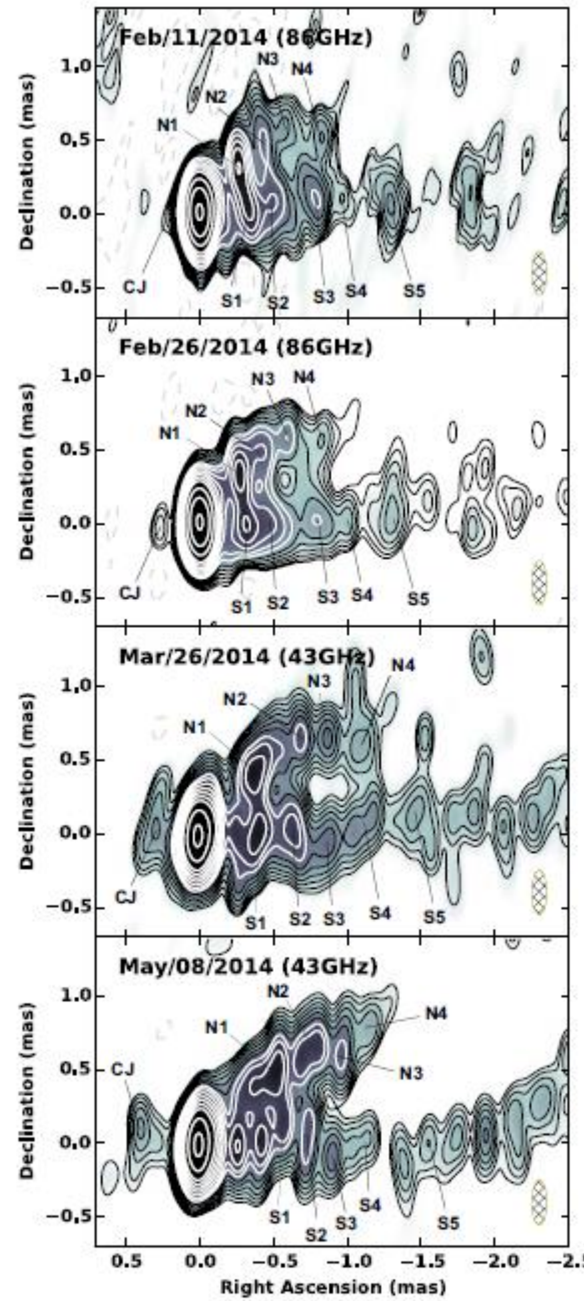
$$M_{BH} = 5.9 \times 10^{9} M_{sun}$$

$$R_S = 2 \times 10^{-3} pc$$



jet base of M87 (VLBA at 43GHz)

Kino et al. 2015 ApJ 803 30

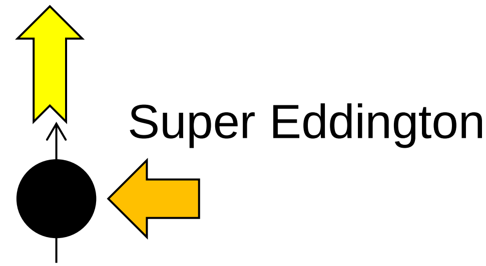


Hada et al. 2015

Physical condition for jet-disk

Naïve picture is wrong

"High mass accretion leads to jet launch"



Observation (? An exceptional source of AGN)

- Very small accretion rate (Prieto et al arXiv:1508.02302)
  very RIAF(Radiative Inefficient Accretion Flow) model
  Jet dominated $L_{disk} / L_{Edd} = 5 \times 10^{-7}$
- Magnetic energy dominated (Kino et al 2015 ApJ 803,30)
  $U_{\pm}(+U_p) << U_B$ -> Magnetically driven jet

BZ process may work

-> A challenge of relativistic MHD for low $\beta(= P_{gas} / P_B)$

Pulsar(NS) vs SMBH

Order of Magnitude

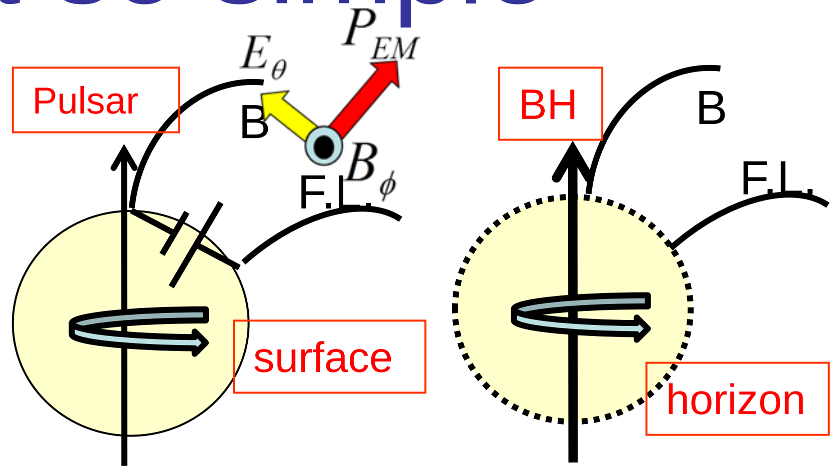
$c = G = 1$

	Pulsar	SMBH (BZ)
Mass (Msun)	M_S	$10^{6-9} M_S$
Size(cm)	$R_S = 10^6$ $\Omega^{-1} = 10^9 P_{0.1}$	$M_{BH} = 10^{14} M_9$
Spin	$\Omega = 2\pi / P$	Kerr Paramater $a_* = a / M$
Bs (Gauss)	10^{12}	10^4
EMF(Max) Volt	$\Delta V \approx BR^3\Omega^2$ $= 10^{14} B_{12} R_6{}^3 P_{0.1}{}^{-2}$	$\Delta V \approx BMa_*$ $= 10^{20} B_4 M_9 a_*$
	dipole	monopole
Power(erg/s)	$P_{em} \approx B^2 R^6 \Omega^4$ $\approx 10^{36} (B_{12})^2 R_6{}^6 P_{0.1}{}^{-4}$	$P_{em} \approx B^2 M^2 a_*^2$ $\approx 10^{45} (M_9)^2 (B_4)^2 a_*^2$

Gamma ray pulsar (10kpc)

M87 (10Mpc) → VHE source?

Analogy is not so simple



Theoretical problem

Origin of E.M.F.

(electromotive force)

Event horizon is passive BC, determined by the exterior (behavior outside BH) $r > r_H$

-> A fundamental problem in BZ process

Origin of VHE flare in M87?

Central BH or Knot

(e.g., Rieger &Aharonian 2012; S de Jong et al 2015)

-> Observational problem solved by CTA

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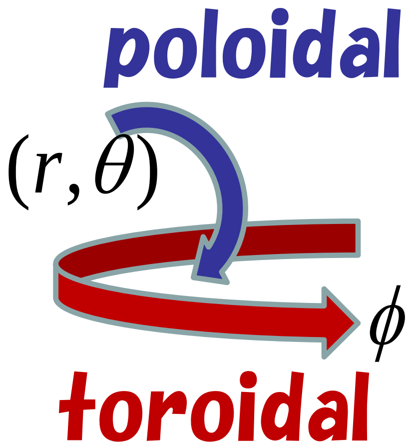
Mathematics of EM dynamics

EM fields in 3+1 formalism

Axi-symmetric and stationary fields



$$\vec{B} = \frac{1}{\varpi}(\vec{\nabla} G \times \vec{e}_{\phi}) + \frac{1}{\alpha\varpi} S \vec{e}_{\phi}$$

$$\vec{E} = -\frac{1}{\alpha}(\vec{\nabla}\Phi - \omega\vec{\nabla} G)$$

E.M.F

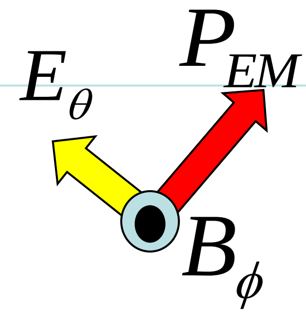
G Magnetic function : poloidal mag.

S Current function : poloidal current flow

Ψ Electric potential : poloidal electric field

Effects of curved spacetime of BH

cont.



- Energy conservation law

$$(\sqrt{-g}T_t^{\ \mu})_{,\mu}/\sqrt{-g}=0$$

-> EM Energy flux in +r direction $\approx(\vec{E}\times\vec{B})_r$

$$4\pi P_r=-\int d\theta d\phi(S\Phi_{,\theta})=-\int(\Omega-\omega)\Omega G_{,\theta}{}^2 d\theta d\phi$$

- Ideal MHD condition

$$\vec{E}\cdot\vec{B}=0\Rightarrow\vec{\nabla}\Phi=\Omega\vec{\nabla}G$$

- Znajek condition (ingoing wave cond)

$$B_{\hat{\phi}}=-E_{\hat{\theta}}\Rightarrow S=(\vec{\nabla}\Phi-\omega\vec{\nabla}G)\varpi/\rho$$

Outgoing power if $0<\Omega<\omega_H$

$$P_{BZ}\approx B^2(a/M)^2M^2$$
$$\approx 10^{45}erg/s(M_9)^2(B_4)^2$$

How realized?

$$0 < \Omega < \omega_H$$

Zero or finite?, a big problem

How are EM fields determined near horizon?

EM power

$$4\pi P_r = -\int d\theta d\phi (S\Phi_{,\theta})_{horizon}$$

$B_\phi(j_p)$ ↑ ↑ E_θ

Origin of electromotive force, E potential difference near horizon, $\vec{\nabla}\Phi = \Omega\vec{\nabla}G$

and polodial current / toroidal mag. S

$$B_p(\leftrightarrow G) \Rightarrow B_\phi(\leftrightarrow S), E_p(\leftrightarrow \Phi)$$

->Consistent EM+plasma flows (this work)

Description of EM fields

(Microscopic) two fluids treatment!

$$\rho_e = e(n_+ - n_-)$$

$$j = e(n_+ v_+ - n_- v_-)$$

✓ It never needs ideal MHD condition, which may be broken elsewhere, $E^2 > B^2$ under a certain condition.

Ideal MHD

$$\vec{E} \cdot \vec{B} = 0 \Rightarrow \Phi(G), \vec{\nabla}\Phi = \Omega \vec{\nabla} G$$

✓It differs from force-free approximation, which may be invalid near horizon.

FF approx.

$$\Rightarrow S(G)$$

Approximations simplify the problem, but are questioned.

$$P = -\tfrac{1}{2}\int d\theta (S\Phi_{,\theta}) \propto \int d\theta (E \times B)_r$$

Model

$$B_p(\leftrightarrow G) \Rightarrow B_\phi(\leftrightarrow S)$$

$$E_p(\leftrightarrow \Phi)$$

Radial magnetic field,
split-monopole

In spherically symmetric case,
radial accretion even for
charged fluids

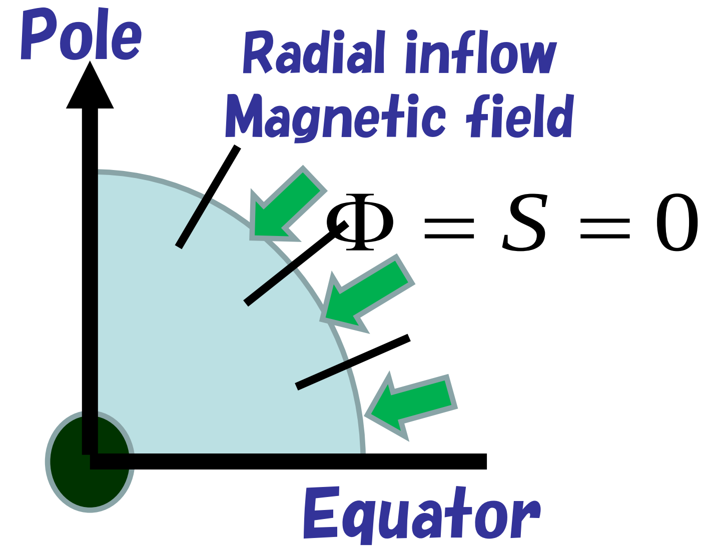
$$\vec{E}=0, \vec{j}=0, \rho_e=0$$

$$\Phi = S = 0$$

everywhere

Taking into account B.H. spin (a) up to the first order

$$\Phi \neq 0 \neq S$$



$$\Phi = S = 0$$

$$P = -\tfrac{1}{2}\int d\theta (S\Phi_{,\theta}) \propto \int d\theta (E\times B)_r$$

Straightforward calculation

MNRAS,454（2015）,3902

Stationary axially symmetric EM and flows determined by four functions G, Φ, F_+, F_-

- Spherical case as background

  -> Radial flow with no charge and current

- Linear pert. w.r.t. spin parameter a*
- Mode decomposition w.r.t. sym. $\delta G = 0$

  -> a coupled ord. diff. eqs for $\delta\Phi, \delta F (= \delta F_+, -\delta F_-)$

- Large/small number χ, κ involved

  -> WKB approximation $\propto \exp(i\chi W(r))$

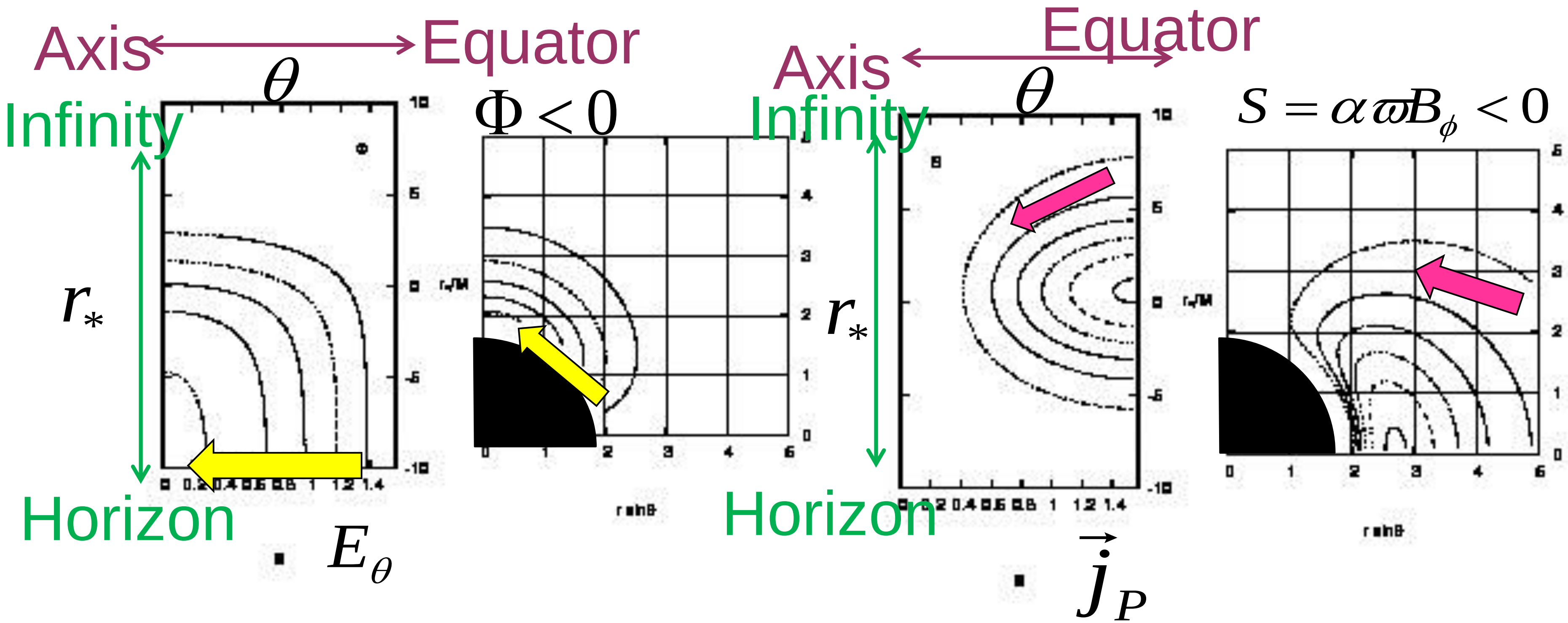
  Many solutions, e.g. Locally oscillating plasma

- Single out radiating mode relevant to BZ

  Results in next page

Results

Electric potential & current function, toroidal magnetic field

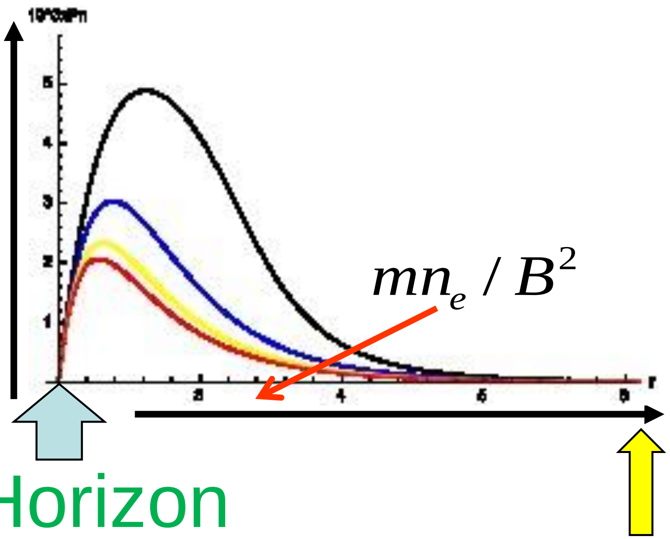


Finite electric field Zero current at horizon

Poynting flux

Outgoing EM Power

$P_{EM}(r)$



EM power through radius r

$$P_{EM}(r) = -\tfrac{1}{2}\int d\theta (S\Phi_{,\theta})$$

Maximum at $r/M \approx 2.5$

EM power originates outside horizon, (ergo-region?)

Sharp shape does not depend on other parameter $\kappa^{-1} \propto \omega_p^{-1}$

Four models shown by colored lines

Comparison

Power

$$P_{BZ} = \frac{2}{3}(1-(\Omega_F/\omega_H))(\Omega_F/\omega_H)B_n{}^2$$

parameter

Maximum $\Rightarrow \frac{1}{6}(a_* B_n GM)^2 c^{-3}$ $\quad 1/6 \approx 0.16$

Present work $\approx 0.08(a_* B_n GM)^2 c^{-3}$

Power is the same order, although EM fields depend on microscopic parameter.

$$\delta B_\phi \propto \kappa a_*, \delta\Phi \propto \kappa^{-1} a_*$$

$$\kappa = \omega_p (GM/c^3) >> 1, \omega_p^2 = 4\pi e^2 n/m$$

Location

Horizon (Ergo-sphere) * r

FF +MHD non-ideal (this work)

Final Question?

Does a central BH play a key role on the jet?

- Correct answer is difficult at present, but we expect to have it by CTA, ALMA, …+theory

Good Luck