Frame Dragging, Unipolar Induction and Jet Source

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Abstract

Unipolar induction [5] is specified by the scalar potential gradient alias the field line angular velocity $\Omega_{\rm F}$, which couples with a Kerr hole's frame dragging angular velocity ω, thereby producing a double-structured magnetosphere consisting of the outer and inner domains. Under the interface $\rm S_N$, there is a magnetized steep gap hidden with the gravito-electric potential drop ΔV and a pair of EMFs $\mathcal{E}_{\rm out}$, $\mathcal{E}_{\rm in}$ due to unipolar induction batteries, where $\mathcal{E}_{\rm out} - \mathcal{E}_{\rm in} = -(\Omega_{\rm H}/2\pi c)\Delta\Psi = \Delta V$. This will give rise to pair-creation discharge of plasma particles ample enough to allow field lines pinned down and to fix $\Omega_{\rm F} = \omega_{\rm N}$ as the eigenvalue in the steady state, keeping magnetized plasma state under the interface $\rm S_N$, and thereby will constitute a power station for launching γ-ray jets.

1 The Blandford -Zanjek Process

Electromagnetic process of extracting Kerr black holes' rotational energy is often referred to as the Blandford-Znajek process, whose efficiency is defined by $\epsilon = \Omega_{\rm F}/\Omega_{\rm H}$, where $\Omega_{\rm F}$ and $\Omega_{\rm H}$ are the field line and the hole's angular velocities [1]. Black hole electrodynamics (BHE) was then reformulated by Thorne et al. in the form of "3+1" formalism [6]. They also proposed "The Membrane Paradigm" [14]. Phinney will be the first who tried to develop a comprehensive model for "black hole-driven hydromagnetic flows" and AGNs, referring to pulsar wind theory [12, 13]. It was considered there that a "magnetized" Kerr hole would posses not only a "battery" but also impedance $Z_{\rm H}$ on the horizon. As seen in "a little table on black hole circuit theory for engineers" and Fig. 3 in [12], the image in the 1980s looks like the magnetosphere consisting of *double* wind structures with *single* circuit with one unipolar induction battery on the horizon. These ideas for the BZ process has invited serious critiques of causality violation.

If the event horizon were *magnetized* in the same way as the neutron star surface of which the "boundary condition" will impose $\Omega_{\rm F} = \Omega_{\rm NS}$, then the boundary condition at the horizon as well would impose $\Omega_{\rm F} = \Omega_{\rm H}$, i.e., $\epsilon = 1$, whereas impedance matching between $Z_{\rm H}$ and Z_∞ is regarded as indicating $\Omega_{\rm F} \approx (1/2)\Omega_{\rm H}$, i.e., $\epsilon \approx 0.5$. This inconsistency comes from presumption of magnetized-ness of the horizon surface under the freezing-in condition, in spite of assuming presence of impedance $Z_{\rm H}$. The dubbed no-hair theorem allows us to know its mass M and angular momentum J only, but will allow none of other macroscopic information to escape from under the horizon, and hence we will be unable to get such non-quantum information as existence of a battery (if any) in the horizon and even of threading field lines.

Latest observational evidences seem to show that the roots of jets come nearer and nearer to the horizon (see e.g. [4]), and related magnetic fields so far seem to be interpreted as associated with rather disk dynamo and the source of jets may be originated at the innermost part of the disk. Our aim of this paper is nevertheless to again spotlight a familiar channel directly related to Kerr holes' rotational energy, that is, the BZ process, and to construct a power station strong enough to launch γ-ray jets by making good use of a Kerr hole's spin-down energy. To achieve the aim, by removing the misunderstandings in the 1980s, we revive the BZ process and the Membrane Paradigm, and design a viable power station with the best cost performance above the horizon, by exploiting EMFs due to unipolar induction batteries to drive electric currents energizing outflows to gamma-ray jets.

2 Black Hole Electrodynamics

At first we presume existence of "perfectly conducting plasma" around a Kerr hole, permeated by "force-free magnetic field" from near the horizon surface S_H to infinity surface S_∞ with the field line angular velocity $\Omega_F(\Psi)$. Force-freeness and frozen-inness combine to indicate that the plasma be charge-separated, and hence $\boldsymbol{j} = \varrho_e \boldsymbol{v}$ in the force-free domains.

Some serious questions we must meet are "where should field lines be anchored, thereby fixing Ω_F?", or equivalently "where is such magnetized matter that allows threading field lines to be anchored and to determine Ω_F in terms of Ω_H through its local frame-dragging angular velocity?". The magnetized matter must simultaneously be current/wind-particle sources for $\boldsymbol{j} = \varrho_e \boldsymbol{v}$ in the *double* current-wind domains (see Fig. 1). This means that the *two* surfaces of magnetized matter must be equipped with *two* EMFs related Ω_F and Ω_H, to drive electric currents in the double circuits. Each current line must, needless to say, constitute a close circuit, starting from one terminal of an EMF and returning to the other terminal with electricity consumed in astrophysical loads (e.g. particle acceleration) or on the resistive horizon membrane (the current-closure condition).

The "3+1" formalism for BHE yields for the poloidal and toroidal components of $\boldsymbol{B}$, $\boldsymbol{E}$, the charge density, the particle velocity and the field line rotational velocity v_F [6, 14, 11],

$$\boldsymbol{B}_p = -(\boldsymbol{t} \times \boldsymbol{\nabla}\Psi)/2\pi\varpi, \quad B_t = -2I/\varpi\alpha c, \tag{1}$$

$$\boldsymbol{E}_p = -(\Omega_{F\omega}/2\pi\alpha c)\boldsymbol{\nabla}\Psi, \quad \varrho_e = (1/4\pi)\boldsymbol{\nabla}\cdot\boldsymbol{E}_p, \tag{2}$$

$$\boldsymbol{v} = \kappa\boldsymbol{B} + v_t\boldsymbol{t}; \quad \boldsymbol{v}_p = \kappa\boldsymbol{B}_p, \quad v_t = \kappa B_t + v_F, \quad v_F = \Omega_{F\omega}\varpi/\alpha, \tag{3}$$

where α is the lapse function/redshift factor, $\Omega_{F\omega} = \Omega_F - \omega$ is the field line angular velocity measured by FIDOs (FIDucial Observers) living in absolute space circulating ω and $\kappa = -(1/\varrho_e\alpha)(dI/d\Psi)$ from equation (4). The two integral functions of Ψ from related differential equations in the steady axisymmetric state, $I(\Psi) = \alpha c\varpi B_t/2$ and $\Omega_F(\Psi)$, are not freely specifiable parameters, but must be determined as the eigen-values (or -functions) of the criticality-boundary condition at the membranes terminating the force-free domains and at the interface S_N between the two domains (see equations (9)$\sim$(11)). Just as every normal coins, Ω_F possesses the two sides, i.e., the field line angular velocity and the scalar potential gradient. Then $\Omega_{F\omega}$ measured by FIDOs as well shows similar two sides, and besides the frame-dragging angular velocity as one side, ω itself gains another side, i.e., the gradient of gravito-*electric* potential V [11]. When ℓ measures distances along each field line Ψ =constant, one can make use of $\omega = \omega(\ell; \Psi)$ as a distance indicator along each field line (see Fig. 1).

Also function $I(\Psi)$ denotes not only the current function, but also the angular momentum flux per unit magnetic flux tube in the force-free domains. The poloidal component of $\boldsymbol{j}_p$ is given by

$$\boldsymbol{j}_p = -(1/\alpha)(dI/d\Psi)\boldsymbol{B}_p, \tag{4}$$

and hence current lines (leads) are defined by $I(\Psi)$ =constant, which coincide with field-streamlines, i.e., Ψ =constant, in the force-free domains. When we require no net gain or loss of charges for a closed surface from the first open field line $\Psi = 0$ to the last open field line $\Psi = \bar{\Psi}$ in the poloidal plane, i.e.,

$$\oint \alpha\boldsymbol{j}\cdot d\boldsymbol{A} \propto I(\bar{\Psi}) - I(0) = 0, \quad \text{i.e.,}\ I(\bar{\Psi}) = I(0) = 0,$$

then $I(\Psi)$ has at least one extremum at $\Psi = \Psi_c$ where $(dI/d\Psi)_c = 0$ (see Fig.2 in [8] for one example of $I(\Psi)$), and hence $\boldsymbol{j}_p \lesseqgtr 0$ for $\Psi \gtreqless \Psi_c$ (see Fig. 1). The field angular momentum flux becomes

$$\boldsymbol{S}_J = [I/2\pi\alpha c]\boldsymbol{B}_p \tag{5}$$

along each field line (see [6, 9, 10]). The Poynting ElectroMagnetic energy flux becomes

$$\boldsymbol{S}_{EM} = (c/4\pi)(\boldsymbol{E}\times\boldsymbol{B}) = [\Omega_{F\omega}I/2\pi\alpha c]\boldsymbol{B}_p = \Omega_{F\omega}\boldsymbol{S}_J \tag{6}$$

(its poloidal component only shown). Related to the outward angular momentum flux, the frame-dragging effect produces a new general-relativistic Spin-Down energy flux $\boldsymbol{S}_{\rm SD}$ [6], and the total flux $\boldsymbol{S}_{\rm E}$ is kept constant independent of ω, and therefore one has

$$\boldsymbol{S}_{\rm SD} = \omega \boldsymbol{S}_{\rm J} = [\omega I/2\pi\alpha c]\boldsymbol{B}_{\rm p}, \quad \boldsymbol{S}_{\rm E} = \boldsymbol{S}_{\rm EM} + \boldsymbol{S}_{\rm SD} = \Omega_{\rm F}\boldsymbol{S}_{\rm J}. \tag{7}$$

The inward Poynting flux in the inner domain plays a role of a kind of *priming water* needed when one wants to pump water out from a well. Relation for $\boldsymbol{S}_{\rm E}$ indicates an equality $\Omega_{\rm F} = (\Omega_{\rm F} - \omega) + \omega$. Note that the origin of $\boldsymbol{S}_{\rm J}$ and $\boldsymbol{S}_{\rm SD}$ are at $\rm S_H$, while that of $\boldsymbol{S}_{\rm EM}$ is at $\rm S_N$ (see Fig. 3 in [9]).

3 Twin Pulsar-Type Winds in Pseudo-Flat Space

When $0 < \Omega_{\rm F} < \Omega_{\rm H}$, there is one identity related deeply to extraction of the hole's rotational energy

$$\Omega_{\rm H} = \Omega_{\rm F} + (\Omega_{\rm H} - \Omega_{\rm F}) = \Omega_{\rm F} - [-(\Omega_{\rm H} - \Omega_{\rm F})], \tag{8}$$

of which the last expresses the difference of $\Omega_{\rm F\omega}$ between $\rm S_\infty$ and $\rm S_H$, i.e., $(\Omega_{\rm F\omega})_\infty - (\Omega_{\rm F\omega})_{\rm H} \equiv \Delta\Omega_{\rm F\omega}$. Note here that $\Omega_{\rm F}$ and $\Omega_{\rm H}$ indicate the scalar potential gradient and the value of gravito-electric potential gradient at the horizon, respectively.

Black hole-driven hydromagnetic flows consist of the out- and in-going winds [1, 12]. Just as the *out*flow ($\boldsymbol{v} = \boldsymbol{j}/\varrho_{\rm e} > 0$) is due to the magnetic sling-shot effect associated with $\Omega_{\rm F}$, the *in*flow ($\boldsymbol{v} = \boldsymbol{j}/\varrho_{\rm e} < 0$) will be so associated with $(\Omega_{\rm H} - \Omega_{\rm F})$, but in order for inflow to be blown magneto-*centrifugally* inward, the field lines will have to rotate oppositely, i.e., $-(\Omega_{\rm H} - \Omega_{\rm F})$. Then identity (8) indicates that the difference of the two angular velocities is $\Omega_{\rm H}$ [see equation (14)].

There must always be some intersurface at $\omega = \Omega_{\rm F}$ in the gravitational potential well of $0 \le \alpha \le 1$ (say $\rm S_N$), where $\Omega_{\rm F\omega} = v_{\rm F} = \boldsymbol{E}_{\rm p} = \boldsymbol{S}_{\rm EM} = 0$ and $\varrho_{\rm e} \approx 0$, changing their sign there. If $\boldsymbol{j}_{\rm p}$ is continuous across $\rm S_N$ along each field line, then $\boldsymbol{v}_{\rm p} \to \pm\infty$ since $\varrho_{\rm e} \to \mp 0$ for $\omega \to \Omega_{\rm F} = \omega_{\rm N}$. This fact shows that the magnetosphere is intrinsically divided by the interface $\rm S_N$ with breakdown of force-freeness into two domains, the outer semi-classical (S-C) domain with $\boldsymbol{S}_{\rm EM} > 0$ and the inner general-relativistic (G-R) domain with $\boldsymbol{S}_{\rm EM} < 0$, according to $\omega \lesseqgtr \Omega_{\rm F}$ and $\Omega_{\rm F\omega} \gtreqless 0$. There must evidently be some particle/current sources coexistent near the interface $\rm S_N$. This situation seems to suggest that there will be two *virtual* spin axes, oppositely directed each other; the axis for outflow is upward, whereas that for inflow must be downward, with the jump of angular velocity as seen in equation (8), and both axes are existent back-to-back at the interface $\rm S_N$ with a magnetized gap between outflow and inflow (see Fig. 1, Secs 4, 5).

In the force-free domains, current lines coincide with field-streamlines, and hence "current-field-streamlines" are equipotentials, with no dissipation taking place at finite distances (from the sources), so that one cannot determine how much current should flow within the force-free domains. It is the criticality condition at the "resitive" membranes $\rm S_{ff\infty}$ and $\rm S_{ffH}$ terminating the force-free domains, containing the fast magnetosonic surfaces $\rm S_{oF}$ or $\rm S_{iF}$ and accelerating zones beyond that determines the current functions $I_{\rm out}$ and $I_{\rm in}$, i.e.,

$$I_{\rm out} = (1/2)\Omega_{\rm F}(B_{\rm p}\varpi^2)_{\rm ff\infty} \ \text{ at } \rm S_{iF} \in S_{ff\infty}, \tag{9}$$

$$I_{\rm in} = (1/2)(\Omega_{\rm H} - \Omega_{\rm F})(B_{\rm p}\varpi^2)_{\rm ffH} \ \text{ at } \rm S_{oF} \in S_{ffH}. \tag{10}$$

The "criticality condition" is equivalent to the "plasma condition" for particles to restore inertia for $|\boldsymbol{v}| \to c$ [7] and Ohm's law for the surface currents on the membranes $\rm S_{ff\infty}$ and $\rm S_{ffH}$ (see [10]). .

As seen in equation (5), the current function $I(\Psi)$ denotes the angular momentum flux per unit flux tube as well in BHE. Because there is no angular momentum source except by extracting through exerting the surface Lorenz torque on the horizon membrane $\rm S_{ffH}$, we may impose continuity of $I(\Psi)$ across $\rm S_N$ between the G-R and S-C domains, i.e. the "boundary condition" $I_{\rm out} = I_{\rm in}$ for the eigenvalue $\Omega_{\rm F}$, and hence we have

$$\Omega_{\rm F} = \Omega_{\rm H}/(1+\zeta), \quad \zeta = (B_{\rm p}\varpi^2)_{\rm ff\infty}/(B_{\rm p}\varpi^2)_{\rm ffH}, \tag{11}$$

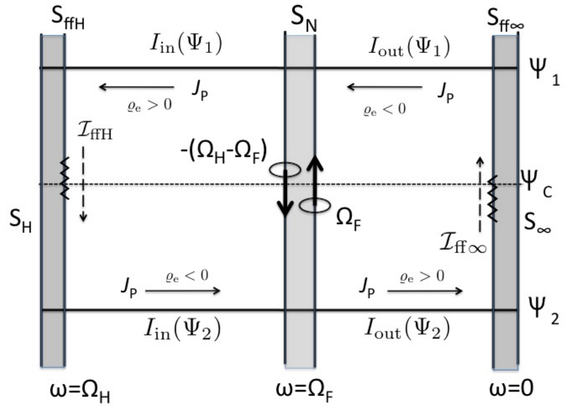

Figure 1: A double-circuit model for the double-structured magnetosphere of a Kerr black hole (cf. [12]). There are the dual unipolar inductors at work with the *virtual spin axes* oppositely directed, of which the angular velocities are $\Omega_{\rm F} \approx 0.5\Omega_{\rm H}$ and $-(\Omega_{\rm H} - \Omega_{\rm F}) \approx -0.5\Omega_{\rm H}$, with difference of $\Omega_{\rm H}$. Note that $\boldsymbol{v}_{\rm p} = \boldsymbol{j}_{\rm p}/\varrho_{\rm e} > 0$ in the outer S-C domain and $\boldsymbol{v}_{\rm p} = \boldsymbol{j}_{\rm p}/\varrho_{\rm e} < 0$ in the inner G-R domain, with the surface of $S_{\varrho_e=0}$ and $|\boldsymbol{v}| \to \infty$ in-between, which leads to breakdown of force-freeness under $S_{\rm N}$ at $\Omega_{{\rm F}\omega} = 0$. Development of a magnetized gap due to a huge voltage drop of ΔV (see equation (14)) will lead to construction of powerful particle/current sources under $S_{\rm N}$. Quasi-neutral plasma particles created in the gap with $\varrho_{\rm e} \approx 0$ will be dense enough to pin down magnetic field lines, to fix $\Omega_{\rm F} = \omega(\ell_{\rm N})$ and make the gap *magnetized*, thereby enabling the dual batteries to drive currents in each circuit (Fig. 2). Joule dissipation of the surface current $\mathcal{I}_{\rm ff\infty}$ in the resistive membrane $S_{\rm ff\infty}$ indicates flow acceleration up to e.g. γ-ray jets, and Joule loss of the surface current $\mathcal{I}_{\rm ffH}$ in the resistive membrane $S_{\rm ffH}$ leading to entropy increase of the hole is the cost for the surface torque due to the surface current $\mathcal{I}_{\rm ffH}$ to extract angular momentum through $S_{\rm ffH}$ from the hole. (Reproduced from Fig. 3 in [11].)

which fixes the location of $S_{\rm N}$ at $\omega = \omega_{\rm N} = \Omega_{\rm F}$ for the outflow-inflow interface. The boundary condition is effectively equivalent to so-called "impedance" matching $Z_\infty = Z_{\rm H}$, and also yields the same result from the "induction" matching, i.e., $\Omega_{\rm F} \approx (\Omega_{\rm H} - \Omega_{\rm F})$ in identity (8), or $|\mathcal{E}_{\rm out}| \approx |\mathcal{E}_{\rm in}|$ by equations (12, 13), and hence $S_{\rm N}$ is at $\omega = \Omega_{\rm F} \approx (1/2)\Omega_{\rm H}$.

It thus turns out that there must be some gap layer of magnetized matter developed due to breakdown of force-freeness, hidden under the interface $S_{\rm N}$, onto which field lines threading $S_{\rm N}$ are pinned down, and this indicates that the matter density must be dense enough for the boundary condition there to ensure $\Omega_{\rm F} = \omega_{\rm N}$. The EMFs related to the magnetized matter under $S_{\rm N}$ with the two *virtual* spin axes will drive currents $\boldsymbol{j} = \varrho_{\rm e}\boldsymbol{v}$ in the force-free domains, as discussed next.

4 Double Circuits

We design Double Circuits, $\mathcal{C}_{\rm out}$ and $\mathcal{C}_{\rm in}$ at $S_{\rm N}$, with two EMFs, $\mathcal{E}_{\rm out}$ and $\mathcal{E}_{\rm in}$, which drive volume currents ($\boldsymbol{j} = \varrho_{\rm e}\boldsymbol{v}$) to flow through the dissipation-free S-C and G-R domains, and then the surface return currents on the resistive membranes $S_{\rm ff\infty}$ and $S_{\rm ffH}$ (see Fig. 1). The two force-free domains separated by the interface $S_{\rm N}$ consist of non-dissipative current-field-streamlines (i.e., equipotentials) with $j_\perp = 0$, and must be terminated by the membranes with resistivity of $\mathcal{R} = 4\pi/c = 377$Ohm, restoring particle inertia with $|\boldsymbol{v}| \to c$. The *volume* currents at finite distances from $S_{\rm N}$ are regarded as *compressed* to the surface cross-field currents across each circle of $2\pi\varpi$ on these membranes at $\varpi \to \infty$ or $\alpha \to 0$, which are given by $\mathcal{I}_{\rm out}$ or $\mathcal{I}_{\rm in} = I(\Psi)/2\pi\varpi$ crossing poloidal field lines leading to Joule-dissipating, implying MHD acceleration on $S_{\rm ff\infty}$ or entropy-production on $S_{\rm ffH}$. The eigenvalues in equations (9, 10) denote Ohm's law for the surface currents flowing across poloidal field lines threading resisitve membranes $S_{\rm ff\infty}$ and $S_{\rm ffH}$ [8].

Let us then pick up such two current-field-streamlines Ψ_1 and Ψ_2 as the two solution of algebraic equation $I(\Psi) = I_{\bar{1}\bar{2}}$, i.e., $I(\Psi_1) = I(\Psi_2) \equiv I_{\bar{1}\bar{2}}$ in the range of $0 < \Psi_1 < \Psi_{\rm c} < \Psi_2 < \bar{\Psi}$ (see Figs. 2, 3

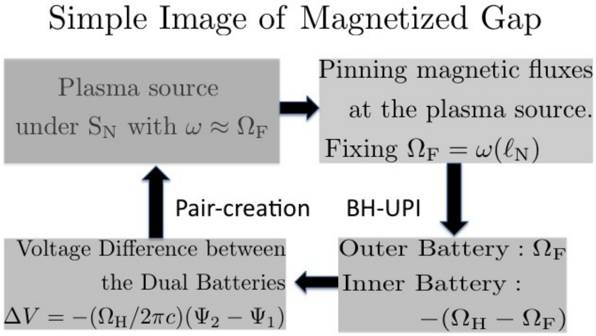

Figure 2: Macroscopic manifestation of effects which frame dragging produces by collaborating with unipolar induction; pinning down magnetic field lines onto the particles created there and fixing Ω_F, thereby producing dual batteries due to BH-UPI (black hole unipolar induction) directed anti-parallel each other, with a huge voltage drop ΔV leading to pair-creation and charge-separation. The new frontier of "gap physics" or "magnetized matter physics", fundamentally different from ordinary vacuum pair-creation discharge mechanism [3] and pulsar gap models so far (see e.g. [2]), will be awaiting to be developed under S_N. (Reproduced from Fig. 4 in [11].)

in [11]), where $(dI/d\Psi)_c = 0$. Faraday integrals along two circuits $\mathcal{C}_{out}$ and $\mathcal{C}_{in}$ yield

$$\mathcal{E}_{out} = \oint_{\mathcal{C}_{out}} \alpha \boldsymbol{E}_p \cdot d\boldsymbol{\ell} = -\frac{1}{2\pi c}\int_{\Psi_1}^{\Psi_2} \Omega_F(\Psi) d\Psi, \tag{12}$$

$$\mathcal{E}_{in} = \oint_{\mathcal{C}_{in}} \alpha \boldsymbol{E}_p \cdot d\boldsymbol{\ell} = +\frac{1}{2\pi c}\int_{\Psi_1}^{\Psi_2} (\Omega_H - \Omega_F) d\Psi. \tag{13}$$

where we utilize equation (2) for $\boldsymbol{E}_p$ with $\Omega_{F\omega} = \Omega_F - \omega$. The difference or gap between the two EMFs existent back-to-back hidden by S_N is

$$\mathcal{E}_{out} - \mathcal{E}_{in} = -\Omega_H \Delta\Psi / 2\pi c = \Delta V \tag{14}$$

where $\Delta\Psi = \Psi_2 - \Psi_1$. Notice that making use of both $\Omega_{F\omega} = \Omega_F - \omega(\ell, \Psi)$ in curved space and $\overline{\Omega_{F\omega}}$ in pseudo-flat space, defined by

$$\overline{\Omega_{F\omega}}(\omega) = \begin{cases} \Omega_F, & \text{for Pulsar-Type Outgoing Wind } (0 \le \omega < \Omega_F), \\ 0, & \text{in Magnetized Gap with } \Delta V \ (\omega = \Omega_F), \\ -(\Omega_H - \Omega_F), & \text{for Anti-Pulsar-Type Ingoing Wind } (\Omega_F < \omega \le \Omega_H), \end{cases} \tag{15}$$

one has the same results for $\mathcal{E}_{out}$, $\mathcal{E}_{in}$ in Faraday path integrals along the circuits $\mathcal{C}_{out}$, $\mathcal{C}_{in}$ as given in expressions (12), (13). Also equation (14) is derivable from identity (8). The frame-dragging effects through $\Omega_{F\omega}(\ell, \Psi)$ in a Kerr hole magnetosphere are thus reproduced through $\overline{\Omega_{F\omega}}(\omega)$ in pseudo-flat space.

5 Black Hole-Driven Jets

Without violating the causality principle, it seems that a Kerr black hole can manage to construct a strong power station at the location with the best cost performance in the deepest potential well, by making full use of frame dragging effects coupled with unipolar induction, to pump out its own rotational energy from the bottom of the well. The "efficiency" is $\epsilon \approx 0.5$ when $\zeta \approx 1$ in equation (11), and if the outer half of the hole's magnetosphere is a pulsar-type one with $\Omega_F \approx 0.5\Omega_H$, in between it and S_H there must be a kind of buffer or boundary layer of relevant size, including the inner domain of double structure and a powerful magnetized gap as particle/current sources. The "inefficiency" $(1 - \epsilon)$ will be due to having to maintain the anti-pulsar-type magnetosphere in the inner domain.

By performing an ingenious trick of turning the outside in with $-(\Omega_{\rm H}-\Omega_{\rm F}) \approx -0.5\Omega_{\rm H}$ in the inner domain, the hole can however reserve its total available resource $\Omega_{\rm H}$ to utilize for constructing the magnetized gap as the power station and launching the flows [see equations (8) and (12, 13)]. This is the way the "inefficient" part of $(\Omega_{\rm H}-\Omega_{\rm F})$ collaborates with the "efficient" part of $\Omega_{\rm F}$, to realize the magnetized gap in between with the total $\Omega_{\rm H}$ for the power station of launching the hydromagnetic flows.

This situation tempts us to make a twin pulsar model with $\overline{\Omega_{{\rm F}\omega}}$ in pseudo-flat space for the scalar potential gradient. We will be able to further presume as if there were two oppositely directed *virtual* spin axes equipped respectively with two magnetic catapults or slingshots for launching outflow $\boldsymbol{v}_{\rm p} > 0$ in the S-C domain and the inflow $\boldsymbol{v}_{\rm p} < 0$ in the G-R domain, with the surface of $S_{\varrho_e=0}$ and $|\boldsymbol{v}| \to \infty$ in-between, which means breakdown of force-freeness. Equivalently there will be the dual unipolar inductors at work, with EMFs $\mathcal{E}_{\rm out}$ and $\mathcal{E}_{\rm in}$, and their huge voltage difference of ΔV will give rise together with necessity of particle supply to development of a magnetized gap. Quasi-neutral plasma particles in the gap will be dense enough to pin down magnetic field lines, to fix $\Omega_{\rm F} = \omega_{\rm N}(\ell_{\rm N})$ and make the gap magnetized, thereby enabling the dual batteries to drive currents in each circuit. It may thus be said that the root of black hole-driven hydromagnetic flows will be at the magnetized gap hidden under $S_{\rm N}$, constructed by joint work of frame dragging and unipolar induction.

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References

[1] Blandford, R.D., & Znajek, R.L., 1977, MNRAS, 179, 465

[2] Beskin, V.S., 2009, MHD Flows in Compact Astrophysical Objects, Springer Heidelberg. p105

[3] Beskin, V.S, Istomin, Ya.N., & Pariev, V.I., 1992, Soviet Astronomy, 36(6), 642
Hirotani, K., & Okamoto, I., 1998, ApJ, 497, 563

[4] Johnson, et al. 2015, Science, 350, 1242

[5] Landau, L.D., Lifshitz, E.M., & Pitaevskii, L.P., 1984, Electrodynamics of Continuous Media, 2nd Ed., Elsevier, Tokyo

[6] Macdonald, D.A, & Thorne, K., 1982, MNRAS, 198, 345

[7] Okamoto, I., 1992, MNRAS, 254, 192

[8] Okamoto, I., 2006, PASJ, 58, 1047

[9] Okamoto, I., 2009, PASJ, 61, 971

[10] Okamoto, I., 2012, PASJ, 64, 50 (There are some typographic errors in equations (24)$\sim$(27): $\Omega_{\rm F}/\Psi$ and I^2/Ψ in there must be changed to $d\Omega_{\rm F}/d\Psi$ and $dI^2/d\Psi$.)

[11] Okamoto, I., 2015, PASJ, 67, 89 (References therein)

[12] Phinney, S., 1983a, in Proc. Torino Workshop on Astrophysical Jets, ed. A. Ferrari & A. Pacholczyk (Dordrecht: Reidel)

[13] Phinney, S., 1983b, Ph.D. thesis, Univ. Cambridge

[14] Thorne, K.S., Price, R.H. & Macdonald, D.A., ed., 1986, Black Holes: The Membrane Paradigm, Yale University Press, New Heaven & London