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Plasma Regimes in the Surroundings of Black Holes, Composite Plasma Disk Structures and Relevant Accretion Processes

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Abstract. The theory of the composite plasma disk structures and of the relevant magnetic field configurations that can surround black holes is presented, consistently with recent experimental observations indicating that highly coherent magnetic field configurations exist in the core of these structures. Concepts developed to describe the physics of magnetically confined laboratory plasmas are used. Thus the “paradox”, that arises when considering accreting plasmas in the presence of a transverse magnetic field is resolved by considering accretion as an intermittent process whereby particles are carried in steps, along a sequence of magnetic separatrixes containing the formed magnetic islands, by the onset of the equivalent of “edge localized modes” (ELMs) observed in laboratory experiments. Inactive galactic black holes are suggested as being associated with older galaxies that have been subjected to collisions destroying the coherent structures needed to guide relevant accretion flows. Alternatively, tridimensional spiral structures can emerge from axisymmetric disk configurations in a region close to the black hole and guide the relevant accretion flows. The radial gradient of the rotation frequency and the vertical gradient of the plasma pressure are the excitation factors for spirals as well as for axisymmetric modes. These can produce vertical flows of thermal energy and particles in opposing directions that can be connected to the winds emanating from disks in Active Galactic Nuclei (AGNs). In the close vicinity of Binary Black Holes the existence of three characteristic plasma regions is envisioned. The intermediate of these regions exhibits three physical regimes that differ both for the magnetic field structure and the spectrum of the emitted radiation, with jets and High Frequency Periodic Oscillations (HFQPOs) produced in two of these regimes.

Keywords: Black Holes, High Energy Plasmas, Accretion Processes

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I. INTRODUCTION

As is well known, important properties of black holes are identified experimentally by the characteristics of the radiation emission [1] from the plasmas that surround them. One of the purposes of this paper is to employ theoretical concepts and

techniques developed in the investigation of magnetically confined laboratory plasmas to deal with the large variety of plasmas that can be associated with black holes and to make a connection with relevant experimental observations. Thus, coherent and stationary plasma and magnetic field configurations [2], collective modes that can be excited under realistic conditions [3] and characteristics of the plasma regimes [1, 4] that can be produced around black holes are introduced and analyzed.

This paper is organized as follows. In Section II the basic equations that describe the equilibrium state of an axisymmetric plasma disk structure are derived. In Section III composite disk structures are identified and described on the basis of the Master Equation for the relevant magnetic field configurations. In Section IV the theoretical issues that arise, when a radial accretion velocity [5] is introduced and a magnetic field configuration with transverse components is present, are pointed out. In Section V the Bursty Accretion process based on the onset of a ballooning instability [6,7] between adjacent separatrices, containing close magnetic surfaces is proposed. In Section VI the plasma regimes and the regions in the vicinity of a Black Hole that can be identified on the basis of the structures considered in the previous sections and of available experimental information are described. In Section VII, the three regimes with three different magnetic field configurations that can be envisioned on the basis of the analyses presented earlier are considered. A set of concluding remarks is given in Section VIII.

II. BASIC EQUATIONS

We start our analysis with asymmetric configurations for which the magnetic field is represented by

$$\mathbf{B} = \frac{1}{R} \left[\nabla \psi \times \mathbf{e}_\phi + I(\psi, z) \mathbf{e}_\phi \right] \quad (\text{II-1})$$

where we use cylindrical coordinates, $\mathbf{B} \cdot \nabla \psi = 0$, and $\psi(R, z) = \text{const.}$ represents the relevant magnetic surfaces. We consider at first the Newtonian limit where General Relativity corrections can be neglected. The plasma is rotating around a central object with a velocity

$$V_\phi = R\Omega(R, z)$$

where

$$\Omega(R, z) = \Omega_k(R) + \delta\Omega(R, z), \quad (\text{II-2})$$

$\Omega_k \equiv (GM_*/R^3)^{1/2}$ is the Keplerian frequency for a central object of mass M_* and whose gravity is prevalent (that is, the plasma self gravity can be neglected) and $|\delta\Omega|/\Omega_k < 1$.

We assume that, in the grand scale, the hyperconductivity condition can be applied in the sense that

$$\mathbf{E}_\Omega + \frac{1}{c} \mathbf{V} \times \mathbf{B} = 0, \quad (\text{II-3})$$

$$\mathbf{E} = \mathbf{E}_\Omega + \Delta\mathbf{E},$$

$$-en \left[\Delta \mathbf{E} + \frac{1}{c} (u_{e\phi} - \Omega R) \mathbf{e}_\phi \times \mathbf{B} \right] - \nabla p_e - \alpha_T n \nabla T_e = 0, \quad (\text{II-4})$$

where the last term represents the thermal force, the plasma resistivity is neglected and $u_{e\phi}$ is the electron flow velocity. Then we take $\mathbf{E}_\Omega = -\nabla \Phi_\Omega(\psi)$, $\Delta \mathbf{E} = -\nabla \Phi_e(\psi) - \Delta U_e$, where

$$-\nabla \Phi_e + \frac{1}{c} (u_{e\phi} - \Omega R) \mathbf{e}_\phi \times \mathbf{B} = 0, \quad (\text{II-5})$$

$$en \nabla U_e - \nabla p_e - \alpha_T n \nabla T_e = 0, \quad (\text{II-6})$$

Clearly, $\mathbf{B} \cdot \nabla U_e \neq 0$. The corresponding equation for the ion population is, for $\rho = m_i n$ and $R \simeq R_0$,

$$-\rho \left(2R_0 \Omega_k \delta \Omega + \frac{3z^2}{2R_0} \Omega_k^2 \right) \mathbf{e}_R + en \Delta \mathbf{E} - \nabla p_i + \alpha_T n \nabla T_e = 0. \quad (\text{II-7})$$

Then the total radial momentum conservation equation is, for $p = p_e + p_i$,

$$-\rho \left(2\Omega_k R_0 \delta \Omega + \frac{3}{2} \Omega_k^2 \frac{z^2}{R} \right) \simeq \frac{\partial p}{\partial R} + \frac{1}{4\pi R_0^2} \left(\frac{\partial^2 \psi_1}{\partial R^2} + \frac{\partial^2 \psi_1}{\partial z^2} \right) \left(\frac{\partial \psi_1}{\partial R} + \frac{d\psi_0}{dR} \right). \quad (\text{II-8})$$

Now, after examining the different options, relating the plasma flow to the magnetic field configurations, we apply the corotation condition $\Omega = \Omega(\psi)$ and obtain

$$2\Omega R \delta \Omega \simeq \left(2\Omega R \frac{d\Omega}{dR} \right) \psi_1 / \left(\frac{d\psi_0}{dR} \right) = -\Omega_D^2 \frac{\psi_1}{d\psi_0/dR}, \quad (\text{II-9})$$

where $\Omega_D^2 \equiv -R d\Omega^2/dR^2 = 3\Omega_k^2$. In the following we consider the limit where the seed magnetic field B_0 is small in comparison to the internal currents generated field, that is $|d\psi_0/dR| \ll |\partial\psi_1/\partial R|$. Clearly, p and ρ are functions of R and z . Then Eq. (II-8) reduces to

$$\rho \left[\frac{3z^2}{2R} \Omega_k^2 + \Omega_D^2 \frac{\psi_1}{(d\psi_0/dR)} \right] + \frac{\partial}{\partial R} \left[p + \frac{1}{8\pi R_0^2} \left(\frac{\partial \psi_1}{\partial R} \right)^2 \right] + \frac{1}{4\pi R_0^2} \frac{\partial^2 \psi_1}{\partial z^2} \frac{\partial \psi_1}{\partial R} \simeq 0, \quad (\text{II-10})$$

in the neighborhood of the surface $R \simeq R_0$.

The total vertical momentum conservation equation is

$$0 \simeq -\frac{\partial p}{\partial z} - z\rho\Omega_k^2 + \frac{1}{c} (J_\phi B_R), \quad (\text{II-11})$$

where $J_\phi = -en(u_{e\phi} - \Omega R)$, and this can be rewritten as

$$0 = -\frac{\partial p}{\partial z} - z\rho\Omega_k^2 - \frac{1}{4\pi R_0^2} \frac{\partial \psi_1}{\partial z} \left(\frac{\partial^2 \psi_1}{\partial R^2} + \frac{\partial^2 \psi_1}{\partial z^2} \right). \quad (\text{II-12})$$

Then we proceed by seeking solutions for ψ_1 on the basis of Eqs. (II-10) and (II-12) for a reasonably prescribed density function $\rho(z^2, R - R_0)$. We observe that a similar procedure was adopted when deriving for the first-time the later called ‘‘pulsar equation’’ that is the magnetic surface equation for a rotating neutron star [8].

III. COMPOSITE DISK STRUCTURES AND THE MASTER EQUATION

The analysis of the disk structures that can be formed in the vicinity of compact objects such as black holes leads to conclude that these are composite structures. These are characterized by a “core” of highly ordered magnetic field configurations with relatively strong fields and a thermal “envelope” where the magnetic field does not play an important role. In fact, there is an increasing body of experimental observations [9] that supports the existence of composite structures. In particular, according to the analysis given below, the core is confined vertically by the Lorentz force due to internal currents while in the envelope the vertical component of the gravity force due to the central object is prevalent.

The Master Equation relates the magnetic surface function to the density profile that characterizes an axisymmetric disk structure. This is derived by applying the $\mathbf{e}_\phi \cdot \nabla \times$ operator to the total momentum conservation equation. We note that

$$\nabla \times \left(-\nabla p + \frac{1}{c} \mathbf{J} \times \mathbf{B} \right) = \frac{1}{4\pi} \nabla \times (\mathbf{B} \cdot \nabla \mathbf{B}) \quad (\text{III-1})$$

and we have

$$\nabla \times \left[\rho (\mathbf{V} \cdot \nabla \mathbf{V}) - \frac{1}{4\pi} (\mathbf{B} \cdot \nabla \mathbf{B}) \right] + \nabla \rho \times \nabla \Phi_G = 0, \quad (\text{III-2})$$

where

$$\Phi_G = -\frac{GM_*}{\sqrt{R^2 + z^2}}, \quad -\nabla \Phi_G \simeq -\frac{V_k^2}{R} \left(\mathbf{e}_R + \frac{z}{R} \mathbf{e}_z \right), \quad V_k^2 \equiv \frac{GM_*}{R}.$$

Then,

$$0 = \frac{\partial}{\partial z} \left[-\rho \left(\frac{V_\phi^2}{R} - \frac{V_k^2}{R} \right) - \frac{1}{4\pi} \left(B_R \frac{\partial}{\partial R} + B_z \frac{\partial}{\partial z} \right) B_R \right] - \frac{\partial}{\partial R} \left[-\frac{1}{4\pi} \left(B_R \frac{\partial}{\partial R} + B_z \frac{\partial}{\partial z} \right) B_z \right] - \left(\frac{\partial}{\partial R} \rho \right) \left(V_k^2 \frac{z}{R} \right) \quad (\text{III-3})$$

that can be rewritten as

$$\frac{\partial}{\partial z} \left[R \rho (\Omega^2 - \Omega_k^2) \right] + \Omega_k^2 z \frac{\partial}{\partial R} \rho + \frac{1}{4\pi} \left[B_z \nabla^2 B_R - B_R \nabla^2 B_z \right] = 0 \quad (\text{III-4})$$

where $\Omega_k \equiv V_k/R$. Thus Eq. (III-4) is the Master Equation and, if we specify Ω as a function of ψ , the particle density distribution ρ becomes the “source” of the relevant magnetic field configuration. Consequently, the relevant pressure profile can be obtained from the vertical equilibrium Eq. (II-12).

After rewriting Eq. (III-4) as

$$2R_0 \Omega_k \frac{\partial}{\partial z} \left[\rho \delta \Omega(\psi_1) \right] + \Omega_k^2 z \frac{\partial}{\partial R} \rho = \frac{1}{4\pi R_0^2} \left[\frac{\partial \psi_1}{\partial R} \left(\nabla^2 \frac{\partial \psi_1}{\partial z} \right) - \frac{\partial \psi_1}{\partial z} \left(\nabla^2 \frac{\partial \psi_1}{\partial R} \right) \right] \quad (\text{III-5})$$

we find it useful to introduce the dimensionless variables $y_* \equiv \psi_1/\psi_N$, $D_* \equiv \rho/\rho_N$, $R_* \equiv R - R_0/\delta_R$, $\bar{z} = z/\Delta_z$, where ψ_N and ρ_N are appropriate normalization quantities, and

$$\delta_R \equiv \left(\frac{R_0}{k_N k_0} \right)^{1/3}, \quad (\text{III-6})$$

where, for $B_0 \equiv (d\psi_0/dR)/R_0$,

$$\frac{1}{k_0} \equiv \frac{B_0}{(4\pi\rho_N)^{1/2} \Omega_D} \quad \text{and} \quad \frac{1}{k_N} \equiv \frac{\psi_N}{R_0^2} \frac{1}{(4\pi\rho_N)^{1/2} \Omega_D}. \quad (\text{III-7})$$

We consider the limit where $B_N \equiv \psi_N/(\delta_R R_0) \gg B_0$, that is

$$\left(\frac{1}{R_0^2 k_2 k_N} \right)^{1/3} = \frac{\delta_R}{R_0} \ll \frac{\psi_N}{R_0 (d\psi_0/dR)} \equiv \varepsilon_0^0 < 1. \quad (\text{III-8})$$

Then we define

$$\varepsilon_N^2 \equiv \frac{\Omega_k^2 \Delta_z^2}{\Omega_D^2 \delta_R R_0} \varepsilon_0^0 \quad (\text{III-9})$$

and consider, for simplicity, $\varepsilon_N^2 < 1$ and, at the same time,

$$c_\Delta^2 \equiv \frac{\delta_R^2}{\Delta_z^2} = \frac{\Omega_k^2 \varepsilon_0^0 \delta_R}{\Omega_D^2 \varepsilon_N^2 R_0} \ll 1. \quad (\text{III-10})$$

Then Eq. (III-5) becomes

$$\begin{aligned} \frac{\partial y_*}{\partial R_*} \frac{\partial}{\partial \bar{z}} \left(\frac{\partial^2}{\partial R_*^2} y_* + c_\Delta^2 \frac{\partial^2}{\partial \bar{z}^2} y_* \right) - \frac{\partial y_*}{\partial \bar{z}} \frac{\partial}{\partial R_*} \left(\frac{\partial^2}{\partial R_*^2} y_* + c_\Delta^2 \frac{\partial^2}{\partial \bar{z}^2} y_* \right) \\ = - \frac{\partial}{\partial \bar{z}} (D_* y_*) + \varepsilon_N^2 \bar{z} \frac{\partial D_*}{\partial R_*}. \end{aligned} \quad (\text{III-11})$$

The ‘‘core’’ region corresponds to $\bar{z} \sim 1$ where Eq. (III-11) reduces to

$$\left(\frac{\partial y_*}{\partial R_*} \right) \frac{\partial^3}{\partial \bar{z} \partial R_*^2} y_* - \left(\frac{\partial y_*}{\partial \bar{z}} \right) \frac{\partial^3}{\partial R_*^3} y_* = - \frac{\partial}{\partial \bar{z}} (D_* y_*) \quad (\text{III-11}')$$

and a relatively simple solution that generalizes that given in Ref. [2] is found for

$$D_*^0 = \frac{3}{2} D_0^0 \frac{\sin^2 R_*}{1 + \varepsilon_* \cos R_*} \exp\left(\frac{-\bar{z}^2}{2} \right) \quad (\text{III-12})$$

where $\varepsilon_* < 1/4$. Correspondingly

$$y_*^0 = D_0^0 \left[\frac{1}{\varepsilon_*} \sin R_* + \frac{1}{2} \sin 2R_* \right] \exp\left(\frac{-\bar{z}^2}{2} \right) \quad (\text{III-13})$$

and the pressure profile is

$$P_*^0 = (D_0^0 \sin R)^2 \left(\frac{1}{\varepsilon_*} + \cos R_* \right) \left(\frac{1}{\varepsilon_*} + 4 \cos R_* \right) \exp(-\bar{z}^2). \quad (\text{III-14})$$

The related temperature profile is represented by

$$T_*^0 = \frac{P_*^0}{D_*^0} \frac{D_0^0}{3\epsilon_*^2} (1 + \epsilon_* \cos R_*)^2 (1 + 4\epsilon_* \cos R_*) \exp\left(\frac{-\bar{z}^2}{2}\right). \quad (\text{III-15})$$

Clearly, as indicated by the expression for \hat{D}_*^0 , the core of the composite structure consists of a sequence of plasma rings. In this context, we note that the resolved X-ray emission from the Crab and of the Vela nebulae by the Chandra space telescope [10] have revealed the existence of a sequence of plasma rings around the pulsars at the center of the relevant nebulae.

Then we may consider the higher order, in ϵ_N^2 , contribution to y_* that is $y_* \approx y^0 + Q(R_*)\epsilon_N^2$. If we take $D_*^0 = D_0^0 F_0(\bar{z}^2) K(R_*)$, referring to Eq. (III-12) and $y_*^0 = D_0^0 F_0(\bar{z}^2) N(R_*)$ and expand $D_* \approx D_*^0 + D_{*2}$ we obtain the following equation for Q

$$\frac{d^3 Q}{dR_*^3} N - \frac{dQ}{dR_*} \frac{d^2 N}{dR_*^2} - KQ = \frac{dK}{dR} + D_{*2} \frac{N}{\epsilon_N^2}. \quad (\text{III-16})$$

We choose $D_{*2} \approx D_{20}$, noticing that $(dK/dR)N \sim \epsilon_*$, where D_{20} is independent of R_* and take

$$D_2^0 = \epsilon_N^2. \quad (\text{III-17})$$

Then Eq. (III-16) reduces to

$$Q''' - \frac{N''}{N} Q' - \frac{K}{N} Q \approx 1 + \frac{dK}{dR} \quad (\text{III-16}')$$

and if we consider an expansion of it in ϵ_* , it has the solution $Q' \approx 1$ corresponding to a vertical magnetic field component. This component generates a field configuration with open and closed magnetic surfaces as indicated in Fig. 1.

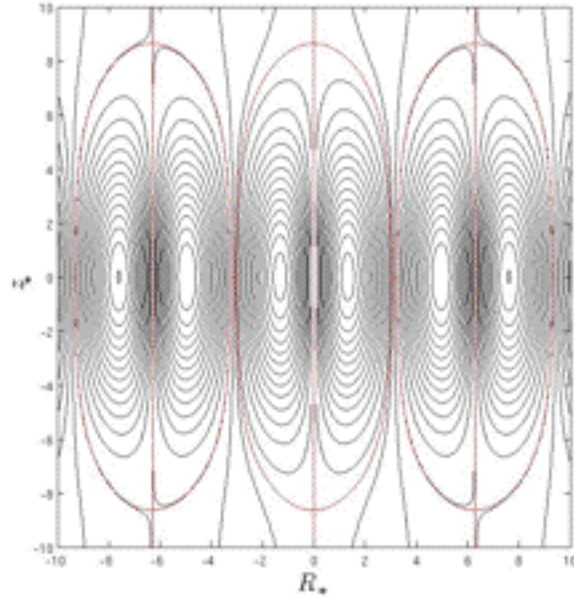


FIGURE 1. Closed and open magnetic surfaces in the core of a composite disk structure.

This present analysis, limited to consider $z \sim \Delta_z$ where

$$\Delta_z = \left(\frac{\delta_R R_0 D_2^0}{\epsilon_0^0} \right)^{1/2} \frac{\Omega_D}{\Omega_k}, \quad (\text{III-18})$$

has been extended to the scale distance $\bar{z} \sim \epsilon_N^{-1}$.

IV. ACCRETION PARADOX

Now we consider the issues that arise when a radial accretion velocity $V_R(R, z)$ is introduced into a magnetized disk structure. This can be estimated from the mass accretion rate \dot{M} as

$$4\pi R \int_0^{H_\infty} dz \rho(R, z) V_R(R, z) = \dot{M}(R),$$

where H_∞ denotes the height of the disk structure. Under strictly stationary conditions ($\partial A_\phi / \partial t = 0$) and in an axisymmetric configuration, the toroidal electric field E_ϕ has to vanish. Then, considering the simplified electron momentum conservation equation $-en(\mathbf{E} + \mathbf{V} \times \mathbf{B}/c) - v_{ei} m_e n(\mathbf{u}_e - \mathbf{u}_i) \approx 0$ the allowed radial velocity is

$$V_R \approx D_m \frac{1}{B_z} \left(\frac{\partial}{\partial R} B_z - \frac{\partial}{\partial z} B_R \right) \quad (\text{IV-1})$$

where $D_m = v_{ei} c^2 / \omega_{pe}^2$ and v_{ei} is the electron-ion momentum transfer rate. Thus $V_R \sim D_m / R$ and if we take the collisional (classical) value for v_{ei} , we have

$$D_m^{cl} \approx 4 \times 10^{-2} \left(\frac{1 \text{ keV}}{T_e} \right)^{3/2} \left(\frac{\ln \Lambda}{15} \right) \text{ cm}^2/\text{s}. \quad (\text{IV-2})$$

It is evident that D_m^{cl} / R is unrealistically low to justify the needed accretion velocities. Therefore, an assumption that is frequently made is that v_{ei} is strongly anomalous [11] that is, larger than its classical value by many orders of magnitudes. In fact, a microinstability, for instance driven by the electron drift velocity, that could produce the needed kind of enhancement is most difficult to envision as the required current density would need to have unrealistically high values.

V. BURSTY ACCRETION

The resolution of the ‘‘accretion paradox’’ that is proposed is based on assuming that a coherent composite structure of the type described in Section III is formed and that the plasma flow is guided by the magnetic field configuration over nearly all of the disk structure. The occurrence of this flow requires the presence of a finer scale angular momentum transport process of contrary direction. In particular: i) the flow velocity \mathbf{V} , that includes a poloidal component, complies with the frozen in condition

$$\mathbf{V} = \alpha_v \mathbf{B}_p + \Omega(\psi) R \mathbf{e}_\phi \quad (\text{V-1})$$

following successive separatrices as indicated in Fig. 2; ii) the plasma is carried from one separatrix to the next by the onset of ballooning modes that are driven by a difference between the gravitational and the centrifugal acceleration; iii) the result is a form of “modulated accretion” associated with the onset of the considered modes and their decay, due to the depletion of the accumulated plasma of the considered modes.

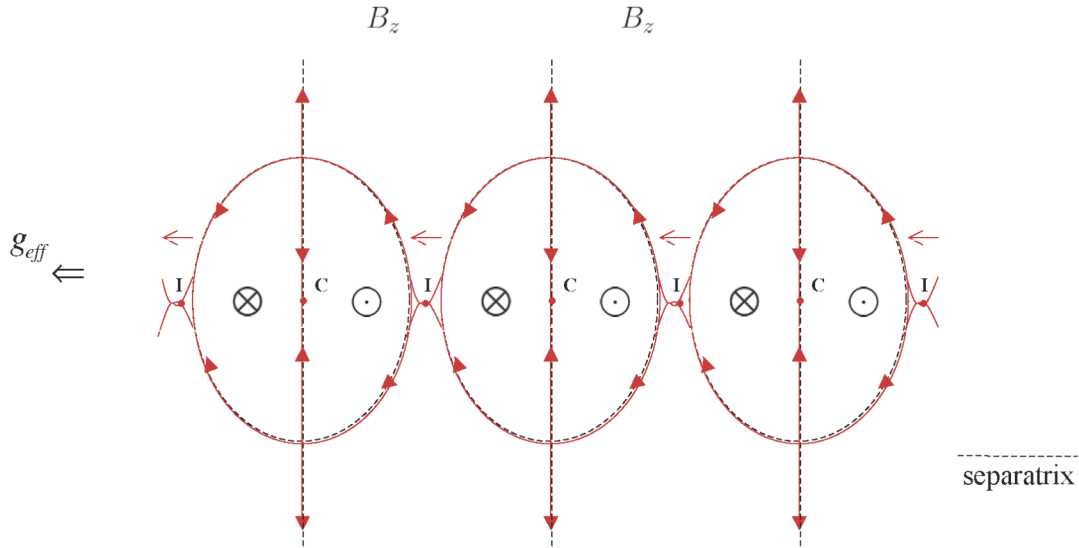


FIGURE 2. Plasma flow patterns according to the Bursty Accretion scenario.

The process that we envision is very similar to that involved in the commonly observed Edge Localized Modes (ELMs) in magnetically confined plasmas. In this case ballooning modes associated with the effects of the plasma pressure gradient at the outer edge of the plasma column are considered to be responsible for the periodic bursts of particles and thermal energy unloaded on the surrounding material wall. As in the case of ELMs the instability growth rate is expected to evolve after the mode onset until most of the density accumulated on one separatrix is unloaded onto the next. Thus accretion proceeds in spurts, populating successive rings until it reaches the innermost plasmas regions that are considered to surround a black hole

This scenario can justify the experimental observation that “inactive” massive black holes at the center of galaxies are more frequent in older galaxies that should have suffered collisions. Thus we argue that coherent magnetic structures of the kind needed for the occurrence of accretion could not survive. Moreover, the result of the envisioned modulated accretion is that successive plasma rings are carried toward the black hole and are ejected in opposite vertical directions (see Fig. 3) depending on the direction of the toroidal currents flowing in them or dissipated within or before reaching the Three-regime Region discussed in Section VII.

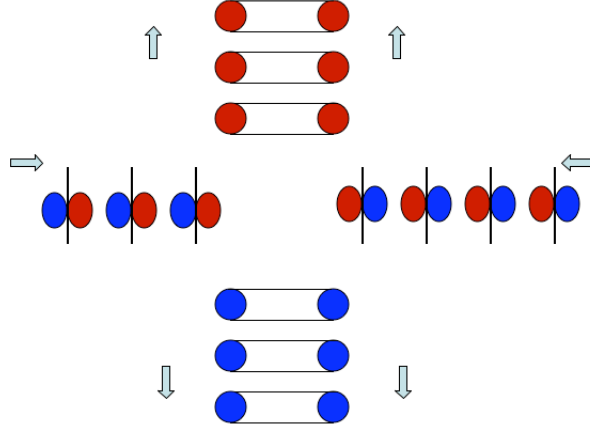


FIGURE 3. Ring ejection scenario.

VI. PLASMA REGIMES AND REGIONS

When considering a non-rotating black hole we can take General Relativity effects into account by adopting an effective potential such as the Paczynski-Wiita gravitational potential

$$\Phi_G \simeq -\frac{GM_*}{R - 2R_G}. \quad (\text{VI-3})$$

where $R_G \equiv GM_*/c^2$. Consequently, in this case, the analysis given in the previous sections can be extended easily to regions that are relatively close to a black hole by adopting the simplified expression (P-W) for Φ_G given above.

When considering rotating black holes, the relevant angular momentum $\mathbf{J} = J\mathbf{e}_z$, is characterized by the dimensionless parameter $a_* = \frac{J}{M_*cR_G}$ with $0 < a_* < 1$,

$a_* \rightarrow 1$ being the so-called “extreme Kerr” limit. In particular, the radius of the marginally stable orbits, R_{Ms} is different for direct and retrograde orbits and is a function of a_* . Specifically when $a_* \rightarrow 1$ (extreme Kerr), $R_{Ms} = R_G$ (for a direct orbit), $R_{Ms} = 9R_G$ (for a retrograde orbit). While, when $a_* = 0$, $R_{Ms} = 6R_G$. Other important radii associated with the Kerr metric to consider are the outermost radius of the ergosphere $R_E^0 = 2R_G$ and the Horizon radius $R_+ = R_G(1 + \sqrt{1 - a_*^2})$. In this case

we may adopt an effective potential [12] for particle orbits in the plane $z=0$ to add General Relativity corrections [13] to the relevant theory.

Now, taking into account the characteristics of the observed radiation emission from black hole candidates, we may envision a sequence of three plasma regions in the vicinity of an “active” a black hole. These regions differ by the kinds of plasma and magnetic field geometry that are present in them. In particular, we consider

- i) a “Buffer Region”
- ii) a “Three-regime Region”
- iii) a “Structured Low Temperature Region”

The inner edge of the Buffer Region is assumed to be at the outermost radius of the ergosphere. This region can be expected to be strongly turbulent and coherent plasma structures originating from external regions should remain excluded from it. We assume that rotational energy extracted from the black hole is deposited in the plasma within this region. Two sub-regions may be identified, separated by the radius of the relevant marginally stable orbit (a.k.a. ISCO).

VII. THREE-REGIME REGION AND STRUCTURED PERIPHERAL REGION

In the region adjacent to the Buffer Region three plasma regimes can emerge. Each regime is characterized both by different particle distributions in velocity space and by different coherent plasma structures. In particular, we may identify

- a) an “extreme” (highly non thermal) regime in which spiral structures are excited.
- b) an “intermediate non-thermal” regime in which plasma ring structures are present and rings are ejected vertically at the inner edge of the region.
- c) a well thermalized regime where the ring structure is gradually dissipated before reaching the inner edge of the region.

In fact, it is well established experimentally, on the basis of the characteristics of the radiation emitted from Binary Black Holes [1] that these can be attributed to 3 states:

- i) a Thermal State, ii) a “Hard” State, iii) a “Steep Power Law” (SPL) State.
- Moreover, transitions between states have been observed for the same object.

In the first regime the plasma is envisioned as characterized by a state of “weak” turbulence associated with the highly non-thermal features of the particle distribution in velocity space. In this regime the ring structures described earlier cannot be maintained. Instead a simple disk structure survives from which spiral modes can be excited. Then accretion is allowed to proceed at a relatively fast rate along these structures to the extent that the relevant plasma densities are relatively low. In particular, plasma spiral modes involve local dips in the plasma density and corresponding temperature increases. Thus we may argue that, in the spiral regions, the plasma degree of collisionality is low and high energy particle populations can form.

We note that spiral modes are excited by the combined effects of the rotation frequency gradient and the vertical pressure gradient [3] and that these modes co-rotate with the plasma at the radius $R = R_0^0$ where Ω_D^2 is largest. We assume that the lowest harmonics $m_\phi = 2, 3$ prevail in their non-linearly developed spectrum. Then we argue [14] that High Frequency Quasi Periodic Oscillations (HFQPO’s) are associated with these modes and have frequencies $2\Omega(R_0^0)$ and $3\Omega(R_0^0)$, respectively,

as observed experimentally. The values of $\Omega(R_0^0)$ that are observed from the experiments for a given black hole of mass M_* indicate that, typically, $R_0^0 > 10R_G$. Therefore, the General Relativity corrections to the theory for the plasmas in this region are relatively modest [4]. We consider the inner radius of the Three-Regime region to be about R_0^0 and the outer radius about $R_0^0 + \Delta_R^s$ where Δ_R^s is the radial width of the spiral modes introduced in Ref. [3].

When the composite disk structure is not dissipated before reaching the Three-regime Region, the excitation of spiral modes is prevented and the associated QPOs disappear. In addition we may argue that as a result of the interaction between the composite disk structure and the strong turbulence at the edge of the Buffer Region the last couple of plasma rings, contained in the same separatrix and carrying oppositely directed toroidal plasma currents that repel each other, are ejected vertically. Following the arguments given in Section V the plasma rings can be expected to “arrive” intermittently with a period related to the onset of the modes that transfer particles from one separatrix to the next.

In particular, we may envision that toroids (“smoke-rings”) carrying currents in the same toroidal directions and attracting each other will be emitted in one vertical direction while toroids carrying currents in the opposite toroidal direction will be launched in the other vertical direction. It is clear that essential jet features such as their extraordinary degree of collimation remain in need of explanation. In this connection we point out that a recent paper [15] suggests that the power associated with jets is independent of the estimated angular momentum of the black holes with which they are associated. The model presented here is consistent with this suggestion. On the other hand it is reasonable to assume that properties of the Buffer Region and of the plasmas contained in it depend on the black hole rotation.

In the third region the plasma is considered to be relatively cold (e.g. well below 1 keV) and in a well thermalized state. In this region a composite disk structure such as that described in Section III is assumed to be well established allowing the (accreting) plasma to flow along successive magnetic separatrices as described in Section V.

VIII. CONCLUDING REMARKS

Composite disk structures, in the surrounding of black holes, have been identified theoretically through a Master Equation of which a set of “rings” solutions have been obtained. These structures are assumed to emerge from the excitation of linearly unstable modes in unstructured (conventional) thin disks. Theoretical concepts and results derived from the analysis of magnetically confined laboratory plasmas have been used in the relevant analysis.

The features of the characteristic plasma regions that are envisioned to develop in the close vicinity of black holes have been described by combining the properties of the observed radiation emission from Binary Black Holes with the evolution of different magnetic field structures. In particular, the plasmas that are formed in one of these regions can exhibit three different regimes where different kinds of structures are coupled with different kinds of spectra of X-ray radiation emission. This is consistent

with the fact that high energy plasmas need be described in the context of phase space (geometry, and momentum).

Clearly, there are numerous relevant issues that remain to be investigated. These include the process of extraction of black hole rotational energy in the context of the envisioned sequence of regions around the black hole, the formation of highly collimated jets following the ejection of plasma rings proposed in Section VII, the origin of the non-thermal electron distributions producing the observed X-ray emission, spectra, etc.

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