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**Gravitational ballooning modes excited by rapidly rotating black hole binaries in parallell to gravitational wave emission.**

COPPI B.
*MIT, MA, USA*

Gravitational ballooning plasma structures are shown to emerge in the close surroundings of rapidly rotating black hole binaries. They are sustained by the time-dependent, non-axisymmetric component of the gravitational potential. These structures are ballooning in the vertical direction and oscillatory in the radial direction. The relevant mode-particle interactions are shown to provide a mean to transfer energy from high- to low-energy particle populations. Thus an explanation can be found for the absence of high energy radiation emission as the collapse of black hole binaries is approached.

* Since the time when focused investigations on Black Holes (BH) were initiated the need to consider them as imbedded in high energy plasmas was recognized (B. Coppi, T. Regge and J. A. Wheeler, I. A. S., 1968) and the first analyses of the plasma configurations that could surround a single BH were undertaken.

* Neutron Star and Black Hole binaries have been predicted and found to sustain the emission of <u>Gravitational</u> <u>Waves</u>.

* <u>Intrinsic Gravitational Modes</u> have been identified which are, likewise, connected to the time dependent, non-axisymmetric component of the gravitational potential of this kind of binaries. These intrinsic plasma modes are tridimensional oscillatory structures that can be sustained in parallel to the (GR) gravitational wave emission.

* Characteristic mode-particle resonant interactions are associated with these modes and

(i) generate high energy particle populations that could be revealed by the observation of periodic high energy radiation emission, or
(ii) transfer energy from independently generated high energy particle populations to low energy [2] thus suppressing a correlated observation of high energy radiation emission.

In fact, a process of this kind can provide an explanation for the persistent lack of observed high energy radiation emission correlated with the emission of gravitational waves corresponding to the collapse of BH binaries.

# Supporting Theory

Gravitational Potential $\left[M_1 = M_2 = M\right.$ for simplicity, with cylindrical coordinates $\left.(R, z, \varphi)\right]$

Define $\quad \Phi_G^{00} \equiv 2\dfrac{GM}{R} \quad \Rightarrow 2\dfrac{GM}{R - r_{sc}}$ (Paczynski – Wiita)

Total Potential

$$\Phi_G \simeq \Phi_G^0(R, z) + \hat{\Phi}_G(R, z, \varphi, t)$$

$$\Phi_G^0 \simeq \Phi_G^{00}\left[1 - \frac{1}{2}\frac{z^2}{R^2}\right]$$

$$\hat{\Phi}_G \simeq -\frac{3}{2}\Phi_G^0 \frac{d_G^2}{R^2}\left(1 - \frac{3}{16}\frac{z^2}{R^2}\right)\cos\left[2\left(\varphi - \Omega_{ob} t\right)\right]$$

$R =$ distance from the C. M. of the binary
$d_G =$ distance between $M_1$ and $M_2$
$R_G \equiv GM / c^2$, $r_{sc} = 2R_G$
$\Omega_{ob} =$ orbiting frequency $\left(\Omega_{ob}^2 \equiv GM / d_G^3\right)$

Consider a distance $R_0 > R_{ISCO}$

$\Omega_K^2 \equiv 2GM / R_0^3$ Keplerian frequency

Flat Stationary Disk (electrons and protons)

$$p_e\left(z^2\right) \sim p_i\,,\;\; n_e\left(z^2\right) = n_i\,,\;\; p_e = nT_e$$

* Electrons Vertical Confinement

$$-enE_z - \frac{dp_e}{dz} = 0 \tag{1}$$

$$E_z = -\frac{d\phi_E}{dz} > 0 \Rightarrow e\frac{d\phi_E}{dz^2} - \frac{1}{n}\frac{dp_e}{dz^2} = 0$$

If $T_e \simeq T_{e0}$,

$$\phi_E \simeq -\phi_E^0\left[z^2/\left(2H_E^2\right)\right], \tag{2}$$

$$n = n_0 \exp\left[-z^2/\left(2H_E^2\right)\right].$$

* Proton (Gravitational) Confinement, for $T_i \simeq T_{i0}$,

$$0 = -z\Omega_K^2 m_i n + enE_z - T_i\frac{dn}{dz}. \tag{3}$$

Therefore

$$\boxed{H_E^2 = \frac{T_e + T_i}{m_i\Omega_K^2}}. \tag{4}$$

In reality we may expect $\phi_E$ to be of a form represented, for instance, by

$$\phi_E \simeq -\phi_E^0\left\{z^2/\left[2H_E^2\left(1+z^2/H_C^2\right)\right]\right\} \tag{2a}$$

where $H_C$, with $H_C^2 >> H_E^2$, is a scale distance characteristic of a low density corona surrounding the disk structures under consideration.

# Intrinsic Gravitational Modes

When a comprehensive analysis of the plasma structures that can be sustained by both the stationary and the oscillatory components of $\Phi_G$, the complete gravitational potential, a tridimensional time dependent plasma structure, can be found that has to be superimposed to the prevailing axisymmetric time independent disk whose peak particle density is $n_0$. This structure can be represented as

$$\hat{\hat{n}} \simeq \tilde{n}_k\left(\overline{z}^2\right)\cos\left[2\left(\varphi-\Omega_{ob}t\right)\right]\cos\left[k_R\left(R-R_0\right)\right] \tag{5}$$

where $\overline{z}^2 \equiv z^2 / H_E^2$,

$$\tilde{n}_k\left(\overline{z}^2\right)=\left(n_k^0/2\right)\left(\tilde{\Omega}_K/\Omega_K\right)^2\left(1-\overline{z}^2\right)\exp\left(-\overline{z}^2/2\right), \tag{6}$$

$\left(\tilde{\Omega}_K\right)^2 / \Omega_K^2 \simeq \left[3d_G / \left(4R_0\right)\right]^2$ and $n_k^0 < n_0$ represents the density corrugation amplitude.

The simplest class of intrinsic gravitational modes is represented by a (rotating) rippling wave with a vertical ballooning structure that corresponds to taking $k_R = 0$ in Eq. (5). As in the case of the conventional flat disk from which it emerges, the mode is considered to be localized around $R = R_0$ over a distance $\Delta_R << R_0$. It can be found when the source of vertical momentum due to the potential $\hat{\Phi}_G$ enters the relevant conservation equation as

$$-zm_i\hat{n}\Omega_K^2 - \left(T_{e0}+T_{i0}\right)\frac{\partial\hat{n}}{\partial z} \simeq zn\left(\overline{z}^2\right)m_i\tilde{\Omega}_K^2\cos\left[2\left(\varphi-\Omega_{ob}t\right)\right] \tag{7}$$

and an oscillatory particle source $\hat{S}_p$ is coupled to the momentum source by the mass conservation equation $\partial\hat{n}/\partial t = \hat{S}_p$. The electron confinement condition corresponding to Eq. (7) reduces to

$$-en_0\tilde{\tilde{E}}_z - 2\left(z/H_E^2\right)T_{e0}\tilde{\tilde{n}}_0\cos\left[2\left(\varphi-\Omega_{ob}t\right)\right]=0.$$

Then, since the electric field acquires the component represented by $\tilde{\tilde{E}}_z$ that is not static, an analysis that includes the associated current densities and magnetic fields is required.

## Example of Relevant Issues

The ballooning feature represented by the $z$- profile (6) with the relevant time dependence can be rewritten as

$$\left(1-\bar{z}^2\right)\exp\left\{-\frac{\bar{z}^2}{2}+i\left[2\left(\varphi-\Omega_{ob}t\right)\right]\right\}\propto\int_{-\infty}^{+\infty}d\bar{k}\bar{k}^2\exp\left(-2\bar{k}^2\right)\exp\left[i\left(\bar{k}\bar{z}-2\Omega_{ob}t+2\varphi\right)\right].$$

Thus the vertical structure is represented as a superposition of oppositely propagating waves with equal frequency but different phase velocities that involve different resonant mode-particle interactions [4]. In particular if energy is transferred to a low energy particle population, the rate of energy transfer is represented by $\bar{\bar{\gamma}}\bar{k}^2$ and the mode is not externally sustained, $\bar{\bar{\gamma}}\bar{k}^2$ would represent the damping rate of the mode $\bar{k}$ –components. In this case the mode profile resulting from a superposition equivalent to Eq. (5) would be $\left(1+\bar{\bar{\gamma}}t\right)^{-1/2}\left[1-\bar{z}^2/\left(1+\bar{\bar{\gamma}}t\right)\right]\exp\left[-\bar{z}^2/\left(1+\bar{\bar{\gamma}}t\right)\right]$. Thus the forcing of the mode by $\hat{\Phi}_G$ should compensate $\bar{\bar{\gamma}}t$ and restore a stationary profile.

[1] E. F. Taylor and J. A. Wheeler, "Exploring Black Holes: Introduction to General Relativity" (Addison Wesley Longman, New York, 2000)
[2] B. Coppi, Plasma Phys. Rep. **45**, 438 (2019)
[3] R. Magee et al., Nature Physics **15**, 281 (2019)
[4] B. Coppi, M. N. Rosenbluth, and R. N. Sudan, Ann. Phys. **55**, 207 (1969)