Physics Letters A 382 (2018) 1283–1286

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

High energy radiation precursors to the collapse of black holes binaries based on resonating plasma modes

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ARTICLE INFO

Article history:
Received 26 January 2018
Received in revised form 15 March 2018
Accepted 16 March 2018
Available online 21 March 2018
Communicated by F. Porcelli

Keywords:
Black holes
Binaries
Precursors
Plasma events
Ballooning modes

ABSTRACT

The presence of well organized plasma structures around binary systems of collapsed objects [1,2] (black holes and neutron stars) is proposed in which processes can develop [3] leading to high energy electromagnetic radiation emission immediately before the binary collapse. The formulated theoretical model supporting this argument shows that resonating plasma collective modes can be excited in the relevant magnetized plasma structure. Accordingly, the collapse of the binary approaches, with the loss of angular momentum by emission of gravitational waves [2], the resonance conditions with vertically standing plasma density and magnetic field oscillations are met. Then, secondary plasma modes propagating along the magnetic field are envisioned to be sustained with mode-particle interactions producing the particle populations responsible for the observable electromagnetic radiation emission. Weak evidence for a precursor to the binary collapse reported in Ref. [2], has been offered by the Agile X-γ-ray observatory [4] while the August 17 (2017) event, identified first by the LIGO-Virgo detection of gravitational waves and featuring the inferred collapse of a neutron star binary, improves the evidence of such a precursor. A new set of experimental observations is needed to reassess the presented theory.

1. Introduction

As is well known, the interpretation of the events producing the gravitational waves [1] detected by the LIGO instrument [2] has been that they involve the collapse of a two black holes binary and, in one case, of a two neutron star binary. The absence of electromagnetic radiation emission coincident with the collapse of black hole binaries, or following it, has led to predict [3] and investigate the possibility that this emission should occur before the collapse.

The conjecture is made that before the collapse a well defined (e.g. disk like) plasma structure is formed around the binary system. This structure can sustain coherent plasma modes that are excited when the orbiting frequency of the two objects increases, as the time of collapse is approached, to the point where it equals that of the frequencies of the modes that can be sustained. We may argue that, if after the two black holes have collapsed, no coherent plasma structure is formed, a high energy radiation emission like that characterizing the precursor event before the collapse would not take place.

In Section 2 a simple plasma structure [5] surrounding a two black hole binary system is introduced. In Section 3 the two-disk plasma density distributions (vertical profiles) that can be associated with the considered binary system are derived. In Section 4 the "Master Equation" is introduced for modes (perturbations) characterized by rapid radial oscillations and a "ballooning" structure in the vertical direction [5]. In Section 5 the "low frequency" magneto-gravitational modes that can be sustained by a plasma surrounding a single black hole are discussed in order to illustrate the characteristics of ballooning mode geometries. In Section 6 the structure of the quasi-tridimensional modes which can resonate with the orbiting frequency of the binary system, is introduced. In Section 7 plasma density and magnetic fluctuations that can be driven by the oscillatory component of the gravitational potential associated with the binary system, are identified. In Section 8 the suggestion is made that the driven modes, which are standing in the vertical direction, decay into oppositely propagating waves. The mode-particle resonance interactions associated with theses waves should create the high energy particle populations [6] needed to produce the high energy radiation emission that should constitute a precursor event.

2. Theoretical model

We analyze a theoretical model involving two black holes [1] with equal masses M orbiting around each other and separated by a distance d. As angular momentum is lost by the system, the

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https://doi.org/10.1016/j.physleta.2018.03.024
0375-9601/

orbit frequency Ω_{ob} of each black hole increases. Our main argument is that this frequency can rise to the point where it matches the frequency of the modes that can be excited in the plasma surrounding the black hole pair.

The gravitational potential associated with the considered binary system [3] is intrinsically tri-dimensional and time dependent, and can be represented as

$$\Phi_G = \Phi_G^0 + \hat{\Phi}_G$$

where

$$\Phi_G^0 = \frac{2GM}{r}\left[1+\frac{d^2}{r^2}\right] \simeq \frac{2GM}{R}\left(1-\frac{1}{2}\frac{z^2}{R^2}\right)\left(1+\frac{d^2}{R^2}\right), \tag{1}$$

$$r=\sqrt{R^2+z^2},$$

$$\hat{\Phi}_G \simeq -\frac{3}{2}\Phi_G^{00}\frac{d^2}{R^2}\left(1-\frac{3}{2}\frac{z^2}{R^2}\right)\cos\left[2(\varphi-\Omega_{ob}t)\right] \tag{2}$$

and $\Phi_G^{00} \equiv 2GM/R$. Clearly, we take $d^2 \ll R^2$, R being the radial distance from the orbit center, and $z^2 \ll R^2$, z being the height above the orbit plane.

Thus

$$\frac{\partial \Phi_G^0}{\partial z} \simeq -\Phi_G^{00}\frac{z}{R^2}, \qquad \frac{\partial \hat{\Phi}_G}{\partial z} \simeq \frac{9}{2}\Phi_G^{00}\frac{d^2}{R^2}\frac{z}{R^2}\cos\left[2(\varphi-\Omega_{ob}t)\right], \tag{3}$$

and, considering a fixed distance $R=R_0$ from the axis of the binary system, the relevant vertical forces surrounding a plasma disk structure are represented by

$$z\rho\Omega_k^2 \quad \text{and} \quad z\rho\varepsilon_k^2\Omega_k^2\cos\left[2(\varphi-\Omega_{ob}t)\right]. \tag{4}$$

Here $\Omega_k^2 \equiv (2GM/R_0^3)$, $\varepsilon_k^2 \equiv (9/2)(d^2/R_0^2)$ and ρ is the plasma mass density. For future use we define also $\tilde{\Omega}_k \equiv \varepsilon_k\Omega_k$. Consequently we have to deal with the three frequencies $\tilde{\Omega}_k < \Omega_k < \Omega_{ob}$.

3. Twin disks configuration

The unperturbed state is characterized by a twin plasma disks configuration as described in the following. We assume, for the simplicity that this configuration is immersed in a constant vertical magnetic field $\mathbf{B}=B\mathbf{e}_z$ and that electrons and nuclei have the same longitudinal (high) temperature $T_\parallel$. Therefore, considering that $\varepsilon_k^2 \ll 1$, to lowest order in this parameter the configuration of interest is stationary. The relevant vertical equilibrium condition, ignoring the effect of the modulated potential Φ_G^0, is

$$-\Omega_k^2 z\rho_h - \frac{2}{m_i}T_\parallel\frac{d\rho_h}{dz} \simeq 0, \tag{5}$$

where $\rho_h \simeq m_i n_h$ with $n_h \equiv n_{ih} = n_{eh}$ represents the density of the "hot" energy particle population (electrons and nuclei) with a temperature independent of z. Then

$$\rho_h(z,R_0) \simeq \rho_h^0\exp\left(-\frac{z^2}{2H_h^2}\right), \tag{6}$$

as is well known, where

$$H_h \equiv \left(\frac{2}{m_i}\frac{T_\parallel}{\Omega_k^2}\right)^{1/2}$$

represents the height of the stationary disk that is sustained by Φ_G^0.

Clearly, the one-fluid Eq. (5) implies that the nuclei are gravitationally confined while the electrons are electrostatically confined. In particularly, for $\mathbf{E}=-\nabla\Phi_E$ we have, at $R=R_0$,

$$-en_h\frac{\partial\Phi_E}{\partial z} + T_\parallel\frac{dn_h}{dz} = 0 \tag{7}$$

implying that

$$\Phi_E \simeq -\frac{T_\parallel}{e}\frac{z^2}{2H_h^2} + B\frac{\Omega_k R_0^2}{c}\ln\left(\frac{R_0}{R}\right) \tag{8}$$

as the radial equilibrium conditions $\mathrm{v}_\phi = \Omega_k R$ leads to identify a radial electric field component given by

$$E_R + \frac{1}{c}\mathrm{v}_\phi B_z \simeq 0. \tag{9}$$

The vertical momentum balance equation to next order in ε_k^2 can be written as

$$-z\left\{\Omega_k^2\hat{\rho}_f + \tilde{\Omega}_k^2\rho_h\cos\left[2(\varphi-\Omega_{ob}t)\right]\right\} \simeq 2\frac{T_\parallel}{m_i}\frac{\partial}{\partial z}\hat{\rho}_f \tag{10}$$

where $\hat{\rho}_f$ is the fluctuating component of the plasma disk structure that can be represented as $\hat{\rho}_f = \varepsilon_k^2\tilde{\rho}_f\cos[2(\varphi-\Omega_{ob}t)]$. Then Eq. (10) becomes

$$-z\{\tilde{\rho}_f + \rho_h\} \simeq H_h^2\frac{d}{dz}\tilde{\rho}_f \tag{11}$$

that has the solution

$$\tilde{\rho}_f \simeq -\frac{1}{2}\frac{z^2}{H_h^2}\rho_h^0\exp\left(-\frac{1}{2}\frac{z^2}{H_h^2}\right) \tag{12}$$

and we observe that the fluctuating component of the density profile is double-peaked in z.

Thus we have a complete expression for the unperturbed density distribution that is

$$\rho_p = \rho_h^0\exp\left(-\frac{1}{2}\frac{z^2}{H_h^2}\right)\left\{1-\varepsilon_k^2\cos\left[2(\varphi-\Omega_{ob}t)\right]\left(\frac{1}{2}\frac{z^2}{H_h^2}\right)\right\} \tag{13}$$

and we observe that the fluctuating component of the density profile is double-peaked. Clearly, in this case the total confining electric field is not electrostatic.

4. Master equation

The Master Equation [5] is obtained from the total momentum conservation equation after applying to it the $\mathbf{e}_\varphi\cdot\nabla\times$ operator. In particular $\mathbf{e}_\varphi\cdot\nabla\times\hat{\mathbf{C}} = -\partial\hat{C}_z/\partial R + \partial\hat{C}_R/\partial z$ and, for

$$\hat{\mathbf{C}} = \tilde{\mathbf{C}}(z)\cos\left[2(\varphi-\omega t)\right]\exp\left[ik_R(R-R_0)\right],$$

we have $\mathbf{e}_\varphi\cdot\nabla\times\hat{\mathbf{C}} \simeq \{-ik_R\tilde{C}_z + d\tilde{C}_R/dz\}\exp[ik_R(R-R_0)+i2(\varphi-\omega t)]$ where $k_R^2R_0^2 \gg 1$.

In this context, using standard notations, we note that the poloidal component of the perturbed total momentum conservation equation is

$$\rho\frac{\partial\hat{\mathbf{v}}}{\partial t} - \frac{1}{4\pi}(\hat{\mathbf{B}}\cdot\nabla\mathbf{B} + \mathbf{B}\cdot\nabla\hat{\mathbf{B}}) + \nabla\left(\hat{p}+\frac{\mathbf{B}\cdot\hat{\mathbf{B}}}{4\pi}\right) + \nabla\cdot(\Delta\hat{\mathbb{P}}) + \hat{\rho}\nabla\Phi_G + \rho(\hat{\mathbf{v}}\cdot\nabla\mathbf{v} + \mathbf{v}\cdot\nabla\hat{\mathbf{v}}) + \hat{\rho}(\mathbf{v}\cdot\nabla\mathbf{v}) = 0, \tag{14}$$

where $\hat{\mathbb{P}} = \hat{p}\underline{\underline{I}} + \Delta\hat{\mathbb{P}}$, and $\Delta\hat{\mathbb{P}} = 0$ if the pressure is isotropic as we assume for a start. Then, considering for simplicity the limit where