Electromagnetic radiation accompanying gravitational waves from black hole binaries

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Abstract. The transition of powerful gravitational waves, created by the coalescence of massive black hole binaries, into electromagnetic radiation in external magnetic fields is considered. In contrast to the previous calculations of the similar effect we study the realistic case of the gravitational radiation frequency below the plasma frequency of the surrounding medium. The gravitational waves propagating in the plasma constantly create electromagnetic radiation dragging it with them, despite the low frequency. The plasma heating by the unattenuated electromagnetic wave may be significant in hot rarefied plasma with strong magnetic field and can lead to a noticeable burst of electromagnetic radiation with higher frequency. The graviton-to-photon conversion effect in plasma is discussed in the context of possible electromagnetic counterparts of GW150914 and GW170104.

Keywords: gravitational waves / experiments, gravitational waves / sources, gravitational waves / theory

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1 Introduction

Recent observations of gravitational waves (GW) by LIGO interferometers \cite{1,2,3} from coalescing black hole (BH) binaries compellingly confirmed two important predictions of General Relativity — the existence of gravitational eaves and astrophysical BHs. The sky localization of GW sources by a network of GW interferometers is limited by long GW wavelengths to a few square degrees \cite{4}, and therefore for the GW astronomy it is important to search for the possible accompanying electromagnetic radiation from the source localization region.

In the observed binary BH coalescences, the energy released in GW amounts to several solar masses. Even if a tiny part of the powerful GW pulse transforms into photons, the effect could be extremely bright. In this connection the transformation of gravitational waves into electromagnetic ones in an external magnetic field \cite{5,6} may create an observable burst of electromagnetic (EM) radiation. Contemporary calculations of this effect with an account for QED and plasma corrections are presented in refs. \cite{7,8}. However in these works the graviton-photon transformation was considered at rather high frequencies, \( \omega/(2\pi) \), exceeding the plasma frequency of the surrounding medium, \( \Omega/(2\pi) \simeq 10 \text{ kHz}\sqrt{n_e} \), where \( n_e \) is electron number density. The reason for that is evident: the low frequency electromagnetic waves with \( \omega < \Omega \) do not propagate in plasma. The only known to us low-frequency example, with \( \omega < \Omega \), was presented in \cite{9}, where the nonlinear generation of higher electromagnetic harmonics in plasma was studied. These harmonics can have sufficiently high frequency allowing them to propagate in the plasma and give rise to potentially observable radio emission.

Importantly, in the case of the LIGO events (the coalescence of binary BHs with 20-30 solar masses) the GW frequency \( \omega/(2\pi) \sim 100 - 200 \text{ Hz} \), and the condition \( \omega < \Omega \) is indeed realized. Nevertheless, the energy transition from the gravitational radiation into electromagnetic energy is still possible. In this paper we show that GWs propagating in plasma with high \( \Omega \) and non-zero magnetic field continuously transform a part of their energy into the non-propagating plasma waves, which can noticeably heat up the plasma and in turn lead to a burst of electromagnetic radiation.

2 GW-to-gamma transformation

The transition of a plane gravitational wave, \( \sim \exp(-i\omega t + ikx) \), into an electromagnetic one in external transverse magnetic field \( B_T \) is described by the equations (see e.g. ref. \cite{7}):

\[
(\omega^2 - k^2)h_j(k) = \kappa k A_j(k) B_T, \quad (2.1)
\]

\[
(\omega^2 - k^2 - m^2)A_j(k) = \kappa k h_j(k) B_T, \quad (2.2)
\]
where $B_T$ is the component of external magnetic field orthogonal to the graviton propagation, subindex $j$ defines the polarization state of the graviton or photon, and $h_j$ is the canonically normalized field of the gravitational wave, such that the kinetic term in the Lagrangian has the form $(\partial_{\mu} h_j)^2$. In other words $h_j$ is related to the metric $g_{\mu\nu} = \eta_{\mu\nu} + \tilde{h}_{\mu\nu}$ according to the relation

$$h_j = \tilde{h}_j / \kappa \quad (2.3)$$

where $\kappa^2 = 16\pi / m_{Pl}^2$, with $m_{Pl} \approx 2 \cdot 10^{19}$ GeV being the Planck mass.

The last term in eq. (2.2) is the effective mass of a photon in the medium. It includes, in particular, the plasma frequency and the Heisenberg-Euler correction. Under the conditions of the problem, $m$ is dominated by $\Omega$:

$$m^2 = \Omega^2 - \frac{2\alpha C \omega^2}{45\pi} \left( \frac{B}{B_c} \right)^2 \approx \Omega^2, \quad (2.4)$$

where $B_c = m_e^2 / e$ is the critical (Schwinger) magnetic field $\simeq 4.4 \times 10^{13}$ G, $e^2 = 4\pi \alpha = 4\pi / 137$, and $C$ is a numerical constant of order unity. It depends upon the relative directions of the magnetic field vector $B$ and the wave polarization. The plasma frequency is equal to:

$$\Omega^2 = n_e e^2 / m_e, \quad (2.5)$$

where $n_e$ is the density of electrons; the contribution of ions is neglected here.

As we have already mentioned, the frequency of the gravitational waves registered by LIGO is small in comparison with the plasma frequency of the interstellar medium. Therefore, in ordinary interstellar medium the second (QED) term in eq. (2.4) can be neglected. However, in the case of larger $\omega$ and/or large magnetic fields the two terms in eq. (2.4) may become comparable and this would lead to a strongly amplified resonance graviton-to-photon transition.

The eigenvalues of the wave vector of the system of equations (2.1), (2.2) are:

$$k_1 = \pm \omega \sqrt{1 + \zeta^2}, \quad k_2 = \pm i m \sqrt{(1 - \zeta^2)(1 - \eta^2)}, \quad (2.6)$$

where

$$\zeta^2 = (\kappa B)^2 / m^2 \ll 1, \quad \eta^2 = \omega^2 / m^2. \quad (2.7)$$

The following eigenfunctions correspond respectively to these eigenvalues:

$$A_1 = \eta \zeta h_1, \quad h_2 = i \zeta A_2. \quad (2.8)$$

The first solution describes a graviton entering into the magnetic field and creating a little photons, while the second one, vice versa, describes a photon which creates a little gravitons in the magnetic field. In the second case the wave vector $k$ is purely imaginary, which corresponds to damping of the electromagnetic wave in plasma when its frequency is below the plasma frequency. In the first case the wave vector $k_1$ is real and the electromagnetic wave does not attenuate and keeps on running together with the gravitational wave, despite its low frequency. The gravitational wave carries the electromagnetic companion and does not allow it to damp.
3 Heating of plasma by the graviton to photon transition

The interaction of an electromagnetic wave with medium is described by the dielectric permittivity $\epsilon$, which determines the relation between the wave vector and the frequency of the electromagnetic wave $k^2 = \epsilon \omega^2$. For the first solution $k \approx \omega$ up to some small corrections of the order of $\zeta^2$. But this is not all. We need to take into account the imaginary part of $\epsilon$, which arises as a result of interactions of the electromagnetic wave with electrons in the medium. This imaginary part leads to transition of energy from the electromagnetic wave into the plasma. For transverse waves in the collisonless plasma, this imaginary part is calculated e.g. in the book [10], the problem 2, eq. (5) after section 31:

$$\text{Im} \, \epsilon = \sqrt{\frac{\pi}{2}} \, \frac{\Omega}{\omega a_e},$$

(3.1)

where $a_e = \sqrt{\frac{T_e}{(e^2 n_e)}} \simeq 743 \sqrt{(T_e/K)/(n_e/\text{cm}^{-3})}$ cm is the Debye screening length for electrons and $T_e$ is their temperature. In the last equation the relation (2.6) $k = k_1 = \omega$ is used.

In the collisionless plasma approximation, this lost energy goes from the GW to the plasma and back. However, an account of the interaction of the electromagnetic wave with the electrons in plasma leads to the heating of the plasma by the energy of the photons which are created by the gravitational wave. If the heating happens to be non-negligible, then an excessive EM radiation from the heated plasma may be registered.

For the interstellar medium with the electron density $n_e = 0.1 \text{ cm}^{-3}$ and the temperature $T_e = 1 \text{ eV}$, the Debye length is approximately equal to $a_e \approx 10^3 \text{ cm} = 3 \cdot 10^{-8}$ seconds, the plasma frequency is about $\Omega \approx 3 \times 10^4 \text{ rad s}^{-1}$, while the frequency of the first registered LIGO event is $\omega \approx 2000 \text{ rad s}^{-1}$. Correspondingly, $\Omega a_e \approx 10^{-3}$ and thus $\omega^2 \text{Im} \, \epsilon \sim \Omega/a_e$ is much larger than $\Omega^2$. Therefore, the amplitude of the electromagnetic wave, carried by the gravitational wave is given by the equation:

$$A_j \approx \frac{\omega a_e k B}{\Omega} h_j$$

(3.2)

So the energy flux of the photons absorbed by the plasma makes the following fraction of the energy flux of the parent gravitational wave:

$$K \equiv \frac{\rho_i}{\rho_{GW}} = \left( \frac{\omega a_e k B}{\Omega} \right)^2 \approx 10^{-46} \left( \frac{\omega}{\Omega} \right)^2 \left( \frac{a_e}{1 \text{ cm}} \right)^2 \left( \frac{B}{1 \text{ G}} \right)^2.$$  

(3.3)

According to [1, 3], the total energy emitted by the gravitational waves is about $3M_\odot$ during approximately 0.01 seconds. So the energy flux of the gravitational waves at the distance $R$ from the source is

$$F_{GW} \approx 100 M_\odot/(4\pi R^2) \text{ per second.}$$  

(3.4)

The frequency of these gravitons (and the produced photons) is a few hundred Hz, which is by far smaller than the temperature of the interstellar or intergalactic media and even smaller than the temperature of CMB (in natural units $c = \hbar = k_B = 1$). Thus, even if the plasma absorbs a lot of energy, the direct heating of plasma by the EM wave would not be efficient. However, this is not all the truth because the electrons in the plasma can be accelerated by the electric field of the running electromagnetic wave and acquire a very large energy. Indeed, the electrons in the electric field of the wave are accelerated according to the equation:

$$m_e \ddot{x}_e = eE = eE_0 \cos(\omega t)$$

(3.5)
and acquire the velocity

\[ V_e \sim \frac{\ddot{x}_e}{\omega} \sim eE_0/(m_e\omega), \]  

where \( \omega \) is of the order of the frequency of the incoming gravitational wave. So the electrons could gain the energy:

\[ E_e = \frac{m_eV_e^2}{2} \sim \frac{e^2E_0^2}{m_e\omega^2}. \]  

This result is true if the electron collision time due to Compton (Thomson) or Coulomb scattering is much longer than the inverse frequency of the wave. This condition is normally fulfilled for the interstellar or intergalactic plasma.

If we take the distance \( R \) equal to the gravitational radius of the black hole with the mass \( 30M_\odot \), i.e. \( R = r_g = 10^7 \text{ cm} \), then the electrons would be accelerated up to the energy \( E_e = 4eV(B/G)^2 \), becoming relativistic for rather mild fields \( B \gtrsim 10^3 \text{ G} \). In such a plasma, \( e^+e^- \) pairs must be created. Their presence would change the values of the plasma frequency and of the Debye length but qualitatively the picture would remain essentially the same.

The above estimate is obtained under assumption of a homogeneous external magnetic field, i.e. for the case where the GW wavelength \( \lambda \) is much smaller than the scale of the field homogeneity, \( l_B \). In the opposite limit the GW-EM conversion effect would be suppressed by the factor \( l_B/\lambda \).

4 Possible observable effects

If such a gravitational wave falls on a magnetar with superstrong magnetic field of about \( 10^{15} \text{ G} \), the produced burst of electromagnetic radiation would be significant for the distances between the magnetar and the coalescing black holes of order of one astronomical unit, which is very small by the astrophysical scales.

Much more plausible could be the burst of electromagnetic radiation if the BH binary itself is surrounded by a medium with sufficiently strong magnetic field. Such a field may be created in analogy with the Biermann battery [11] induced by the rotating space-time around the binary due to the different mobility of protons and electrons in the surrounding bath of electromagnetic radiation (see, e.g., [12] discussing the battery effect in application to the origin of the seed magnetic field in rotating protogalaxies immersed in an isotropic CMB photon field). In the battery mechanism on thermal electrons, the amplitude of the magnetic field is directly proportional to the energy density of photons \( \epsilon_\gamma \):

\[ \frac{e}{m_e c}B \sim \frac{4}{3} e\sigma_T \frac{e_\gamma}{m_e c^2} (2\omega_{LT} \Delta t) + B_0, \]

where \( B_0 \) is the initial magnetic field in the plasma, \( \sigma_T \) is the Thomson cross-section, \( \omega_{LT} \) is the Lense-Thirring frequency, \( \Delta t \) is the field growth time (in this formula the velocity of light \( c \) is recovered). Clearly, in the problem under consideration \( \omega_{LT} \Delta t \sim 1 \), and for typical interstellar (or CMB) photon energy density \( \epsilon_{CMB} \sim 1 \text{ eV cm}^{-3} \) the produced field is insignificant:

\[ B \sim 2 \times 10^{-27}[\text{G} \left( \frac{\epsilon_\gamma}{\epsilon_{CMB}} \right)] + B_0. \]

The linear dependence of the battery effect on photon energy density suggests the most favorable sites for GW-EM conversion in the vicinity of strong radiation sources or in a hot plasma. For example, if a BH-BH merging happens close to an active galactic nucleus with
typical luminosity of $\sim 10^{44}$ erg/s, $\epsilon_\gamma \sim L/(R^2c) \sim 2 \times 10^8(L/10^{44}\text{erg s}^{-1})(R/1\text{pc})^2\text{eV cm}^{-3}$. In a hot rarefied cosmic plasma with $T \sim 10$ keV (e.g., in galaxy cluster centers) $\epsilon_\gamma \approx \tau(T/T_{\text{CMB}})^4\epsilon_{\text{CMB}}$, where $\tau$ is the characteristic optical depth. In our problem, $\tau \sim \Lambda_{\text{em}}\sigma_T$, so that $\epsilon_{\gamma}/\epsilon_{\text{CMB}} \sim (H_0/\omega)(T/T_{\text{CMB}})^4 \sim 10^{15}$. Both estimates, however, show that in real astrophysical conditions the battery effect could hardly lead to the fields which are interesting for the efficient GW-EM conversion.

The rate of binary BH coalescences derived from LIGO observations is $\sim 12$ per cubic Mpc per year [3]. This rate is orders of magnitude smaller than the rate of bright short electromagnetic transient phenomena, such as short gamma-ray bursts (SGRB, about one per few days for distances up to a few Gpc) or enigmatic fast radio bursts (FRB, a few thousand per day for distances up to hundreds Mpc). The mean energy emitted by an FRB is $\Delta E_{FRB} \approx 10^{38}$ ergs [13]. Even to intercept this energy from a BH-BH merging, the magnetar should occur within a planetary system distance of a few astronomical units, which is quite improbable. The SGRB phenomenon, in turn, with a typical EM energy release of $10^{49}$ erg, is likely to be unrelated to BH-BH mergings [14].

However, the close time occurrence of a faint Fermi GBM event $\sim 0.5$ s after GW150914 [15] and the recent AGILE observation of the possible short MeV burst preceding the final coalescence of GW170104 by $\sim 0.5$ s [16], if real, may suggest an efficient EM energy release during BH-BH coalescence. A possible scenario is proposed in [17] assuming fragmentation of the collapsing core of a rapidly rotating star. The GW-EM conversion mechanism discussed in the present paper suggests that for the plausible conditions of dense plasma disk surrounding a coalescing compact binary (see, e.g., the discussion in [18]) the magnetic field can reach the equilibrium values $B^2/(8\pi) = \epsilon_B\rho$ and be as high as $10^{15}$ G for $\epsilon_B \sim 1$. Under the extreme conditions discussed in [18], the electron temperature is limited to the pair creation values $T = \epsilon_T m_e$ with $\epsilon_T \sim 1$, and the Debye length is thus $a_e^2 \sim \epsilon_T (m_e m_p)/(4\pi\alpha \rho) = \epsilon_T/\Omega^2$. Plugging these extreme values into equation (3.3), we find the limit GW-EM efficiency conversion coefficient

$$K \leq \epsilon_B \epsilon_T \frac{32\pi}{\alpha} \left(\frac{\omega}{\Omega}\right)^2 \left(\frac{m_e}{m_p}\right)^2 \left(\frac{m_p}{m_{\text{pl}}}\right)^2 \sim 10^{-37} \epsilon_B \epsilon_T \ll 1. \quad (4.3)$$

The small factor $(\omega/\Omega)^2$ further diminishes this estimate, taking into account the GW frequency at the peak GW emission being around twice the Keplerian orbital value prior to the merging $\omega^2 \sim (1/2)(m_{\text{pl}}/M)^2 m_e^2$, where $M$ is the total mass of the coalescing binary:

$$\left(\frac{\omega}{\Omega}\right)^2 \simeq \frac{1}{2} \left(\frac{m_{\text{pl}}}{M}\right)^2 \frac{m_{\text{pl}}^2 (m_e^2)}{4\pi\alpha \rho} \approx \left(\frac{3M_{\odot}/M}{M}\right)^2 \left(\frac{\rho}{10^{-24}\text{g cm}^{-3}}\right)^{-1}. \quad (4.4)$$

For GW-EM conversion regime in plasma considered here to be applicable, the GW to plasma frequency ratio $\omega/\Omega$ ratio should be smaller than one, suggesting the total BH-BH binary lower mass limit $M \gtrsim 3M_{\odot}/\sqrt{\rho/10^{-24}\text{g cm}^{-3}}$, which obviously holds for solar-mass BH-BH binaries in any realistic astrophysical conditions.

Thus, we conclude that the GW-EM conversion effect in plasma considered here can hardly provide significant plasma heating in LIGO BH-BH coalescences and explain the observed EM power in gamma-ray events possibly associated with GW150914 and GW170104 mentioned above. However, the effect (3.3) may turn out to be substantial in hot rarefied plasma where the strong external magnetic field is dynamically unrelated to the plasma density (e.g. near the magnetars).
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