Electromagnetic phenomena around black holes.

A. D. Dolgov

Novosibirsk State University, Novosibirsk, Russia
ITEP, Moscow, Russia

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Outline

Content of the talk:

I. Gravitational waves (GW) transformation to photons in magnetic field of coalescing black hole binary.
AD and K. Postnov, JCAP 1709 (2017) no.09, 018; arXiv:1706.05519

II. A mechanism of magnetic field generation around BH binary. C. Bambi and AD (prelimenary).

GW registered by LIGO

LIGO (and Virgo) have detected 15 events of GWs. Typical (first) case:

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1 + z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

GW registered by LIGO

The mass and spin of the final BH, and the total energy radiated in gravitational waves are estimated by the fits to numerical simulations of binary black hole mergers.
The estimated total energy radiated in gravitational waves is $(\mathbf{3.0 \pm 0.5}) M_\odot$ and a peak of gravitational-wave luminosity is $\mathbf{3.0^{+0.5}_{-0.4} \times 10^{56}}$ erg/sec equivalent to $\mathbf{200} M_\odot$/sec, more than whole radiation power of the visible universe.

Even if a small fraction of GW energy is transformed into electromagnetic radiation, it may be detectable and tell a lot about the media around the BH binary. One needs to know the direction to the source. With two effective detectors only one angle out of two is determined. At least one more detector is badly needed.

Transition $g \leftrightarrow \gamma$ in magnetic field

Production of gravitational waves by photons in magnetic field, M.E. Gerzenstein *ZhETF*, **41** (1961), 113 [*Sov. Phys. JETP*, **14** (1961). 84]. Transformation of gravitational waves to electromagnetic radiation in magnetic field, Ya.B. Zeldovich, *ZhETF*, **65** (1973), 1311 [*Sov. Phys. JETP*, **38** (1974), 652. Contemporary theory in Raffelt and Stodolsky, , Phys. Rev. D 37 (1988) 1237.

The transition of a plane gravitational wave, $\sim \exp(-i\omega t + i\mathbf{k}\mathbf{x})$, into an EM one in external transverse magnetic field B_T is described by:

$$(\omega^2 - k^2) h_j(\mathbf{k}) = \kappa k A_j(\mathbf{k}) B_T \,,$$

$$(\omega^2 - k^2 - m_\gamma^2) A_j(\mathbf{k}) = \kappa k h_j(\mathbf{k}) B_T \,,$$

j describes the polarization of the graviton or photon, and h_j is canonically normalized field of GW, such that the kinetic term has the form $(\partial_\mu h_j)^2$, i.e. h_j is related to the metric $g_{\mu\nu} = \eta_{\mu\nu} + \tilde{h}_{\mu\nu}$ according to the relation

$$h_j = \tilde{h}_j / \kappa, \;\; \kappa^2 = 16\pi / m_{Pl}^2, \;\; m_{Pl} \approx 2 \cdot 10^{19}\,\mathrm{GeV}.$$

Transition $g \leftrightarrow \gamma$ in magnetic field

The m_γ term in equation above is the effective mass of photon in the medium. It includes the plasma frequency Ω and the Heisenberg-Euler correction. Under the conditions of the problem, m_γ is dominated by Ω:

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

where $B_c = m_e^2/e$, $e^2 = 4\pi\alpha = 4\pi/137$. and C is a numerical constant of order unity. It depends upon the relative directions of the vector $\mathbf{B}$ and the wave polarization. The plasma frequency is equal to:

$$\Omega^2 = n_e e^2/m_e,$$

n_e is the density of electrons; ions are neglected here.

Transition $g \leftrightarrow \gamma$ in magnetic field

COMMENT: the frequency of the gravitational waves registered by LIGO is small in comparison with the plasma frequency of the interstellar medium. That's why the second term in eq. for m_γ can be neglected. However, in the case of larger ω and/or large magnetic fields the two terms in this eq. may become equal and this would lead to a strongly amplified resonance transition of graviton to photon (analogous to MSW resonance in neutrino oscillations).

Transition $g \leftrightarrow \gamma$ in magnetic field

The eigenvalues of the wave vector of the system of equations:

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

where

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

To this eigenvalues correspond respectively the following eigenfunctions:

$$A_1 = \eta\,\zeta h_1, \;\; h_2 = i\zeta A_2.$$

A_1 describes graviton entering into magnetic field and creating a little photons, while h_2 describes photon creating a little gravitons. In the second case the wave vector k_2 is purely imaginary, corresponding to damping of EM waves when $\omega < \Omega$. 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, despite $\omega < \Omega$.

Transition $g \leftrightarrow \gamma$ in magnetic field

Heating the plasma by e.m. wave created by GW.

The interaction of electromagnetic wave with a medium is described by the dielectric permittivity ϵ: $k^2 = \epsilon\omega^2$. For the first solution $k \approx \omega$ up to some small corrections of the order of ζ^2. To estimate the photon loss of energy due to electron heating we need know imaginary part of ϵ.

According e.g. to Landau-Lifshitz book, for the transverse wave this imaginary part is

$$\mathrm{Im}\,\epsilon = \sqrt{\frac{\pi}{2}}\,\frac{\Omega}{\omega k a_e} \approx \sqrt{\frac{\pi}{2}}\,\frac{\Omega}{\omega^2 a_e},$$

where $a_e = \sqrt{T_e/(4\pi e^2 n_e)}$ is the Debye screening length for electrons and T_e is their temperature.

Transition $g \leftrightarrow \gamma$ in magnetic field

In the approximation of the collisionless plasma this lost energy goes from the wave to the plasma and back. However, an account of the electron collisions leads to the heating of the plasma by the energy of the photons which are created by the gravitational wave. Hence an excessive electromagnetic radiation from the heated plasma may be registered.

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

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

Transition $g \leftrightarrow \gamma$ in magnetic field

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

$$K \equiv \frac{L_\gamma}{L_{GW}} = \left(\frac{\omega a_e \kappa B}{\Omega}\right)^2 .$$

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

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

So, $K \ll 1$ and the direct heating of the plasma would be negligible in the objects at reasonable distances.

Transition $g \leftrightarrow \gamma$ in magnetic field

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 got a very large energy. Indeed, the electrons in the electric field of the wave are accelerated according to the equation:

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

and acquire the velocity

$$V_e \sim \ddot{x}_e/\omega \sim eE_0/(m_e\omega),$$

So the electrons could gain the energy:

$$\mathcal{E}_e = \frac{m_e V_e^2}{2} \sim \frac{e^2 E_0^2}{m_e \omega^2}.$$

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.

Transition $g \leftrightarrow \gamma$ in magnetic field

If we take the distance R equal to the gravitational radius of the black hole with the mass 30 $M_\odot$, i.e. $R = r_g = 10^7$ cm, then the electrons would accelerate up to the energy $\mathcal{E}_e = 4\mathrm{eV}(B/\mathrm{Gauss})^2$, becoming relativistic for rather mild fields $B \gtrsim 10^3$ Gauss. In such 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 presented above estimate is obtained under assumption of homogeneous external magnetic field, i.e. for the case when the wave length λ is much smaller than the scale of the field variation, l_B. In the opposite limit the effect would be suppressed by the factor l_B/λ.

Transition $g \leftrightarrow \gamma$ in magnetic field

If such a gravitational wave heats a magnetar with magnetic field about $\mathbf{10^{15}}$ G, the produced burst of electromagnetic radiation would be significant for the distances between the magnetar and the coalescing black holes up to $\mathbf{10^{-5}}$ parsec, which is very small by the astrophysical scales.

Much more powerful could be the burst of electromagnetic radiation if the black hole binary is surrounded by the medium with sufficiently strong magnetic field. Such a field may be created by an analogue of the Biermann battery induced by the rotating binary due to the different mobility of protons and electrons in the surrounding bath of electromagnetic radiation.

Magnetic field generation around rotating binary

C. Bambi and A.D. (preliminary)
As is known that the difference between masses of proton and electron results in four million times difference of their elastic scattering on photons and hence in a difference of their mobilities in interstellar plasma. Thus it leads to predominant capture of protons by celestial bodies, making them electrically charged (Shwarzman mechanism of star charging).
Accordingly the interstellar medium around a star becomes electrically charged. Rotating locally charged sphere creates non-zero magnetic fields.
Normally the strength of such magnetic field is given by the Biot-Savart law. However in astrophysical systems the time of establishment may be too high (see Berezhiani, AD, Tkachev, 2013).

Magnetic field generation around rotating binary

Bambi, AD, Petrov, JCAP 0909 (2009) 013 - charging of stellar bodies

Let us consider a BH of mass M surrounded by plasma of protons and electrons. In the simplest case of perfect spherical symmetry, the radial part of the equations of motion for the proton and electron fluids are

$$\dot{v}_p = -\frac{G_N M}{r^2} + \frac{\alpha Q}{r^2 m_p} + \frac{L\,\sigma_{\gamma p}}{4\pi r^2 m_p} - \frac{\sigma_{\gamma p} n_\gamma \omega_\gamma}{m_p}\, v_p - \frac{n_p \sigma_{pe} P}{m_p}\,(v_p - v_e),$$

$$\dot{v}_e = -\frac{G_N M}{r^2} - \frac{\alpha Q}{r^2 m_e} + \frac{L\,\sigma_{\gamma e}}{4\pi r^2 m_e} - \frac{\sigma_{\gamma e} n_\gamma \omega_\gamma}{m_e}\, v_e + \frac{n_e \sigma_{pe} P}{m_e}\,(v_p - v_e)\,.$$

Here $\boldsymbol{v_p}$ and $\boldsymbol{v_e}$ are the proton and electron regular velocities, $\boldsymbol{Q}$ is the electric charge of the BH in proton charge units, $\alpha = e^2/4\pi = 1/137$, L is luminosity in the comoving frame of the accretion flow, P is the momentum transfer in ep–scattering, n_p and n_e are the number densities of $\boldsymbol{p}$ and $\boldsymbol{e}$, $\boldsymbol{n_\gamma}$ is the photon number density and ω_γ is the photon energy.

Magnetic field generation around rotating binary

Z.Berezhiani, AD, I.Tkachev, "Dark matter and generation of galactic magnetic fields", The European Physical Journal, C73 (2013) 2620.
The Biot-Savart law is valid only when the stationary regime is reached, but the system under scrutiny may be far from that. To see that let us consider the Maxwell equations in the cosmological plasma and modification of the MHD equations in presence of extra non-potential forces related to a dark matter interaction with electrons. Namely, let us consider the electric current

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{F}/e),$$

where $\boldsymbol{F}$ is the external force acting on electrons, $\boldsymbol{F} = e\boldsymbol{v}\boldsymbol{B_F}$ where the factor B_F can be estimated as $\boldsymbol{B_F} = \sigma_{e\gamma} n_\gamma \omega_\gamma / e$.

Magnetic field generation around rotating binary

Finding electric field $\boldsymbol{E}$ from the equation for J in the previous page and substituting it into equation $\partial_t \boldsymbol{B} = -\boldsymbol{\nabla} \times \boldsymbol{E}$, we obtain

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{F}/\mathbf{e} + \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{1}{4\pi\sigma}(\boldsymbol{\Delta} \boldsymbol{B} + \partial_t^2 \boldsymbol{B}),$$

which is in fact the MHD equation in the presence of external source term

$$\boldsymbol{\nabla} \times \boldsymbol{F}/\boldsymbol{e} = \boldsymbol{B_F} \boldsymbol{\nabla} \times \boldsymbol{v} + (\boldsymbol{\nabla} \boldsymbol{B_F}) \times \boldsymbol{v}.$$

In the limit of high conductivity, the second term in the MHD equation, the so called advection term, leads to a dynamo effect on the magnetic seed fields once the value of the latter is non-zero. It is well-known, however, that in absence of the source term, the MHD equations cannot give rise to non-zero magnetic field if $\boldsymbol{B} = 0$ initially.

Magnetic field generation around rotating binary

In our case, assuming $\boldsymbol{B} = 0$ at $t = 0$, we find that the source term induces a nonzero magnetic seed field which initially grows roughly as

$$\boldsymbol{B(t) = \int_0^t dt\, \nabla \times F/e = \int_0^t dt\, \nabla \times (B_F v)\,.}$$

Then one can estimate the strength of field generated near rotating binary of black holes with masses about 20-30 solar masses to be around $\mathbf{10^{10} - 10^{13}}$ Gauss. However, this rough preliminary estimate may too optimistic.

Neveetheless there is a lot of room to retreat still remaining with observable effect, especially if the position of the binary is established with the next generation of GW detectors.