Fermi GBM signal contemporaneous with GW150914 - an unlikely association

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ABSTRACT

The physical constraints required by the association of the Fermi GBM signal contemporaneous with GW150914 - radiative power of $10^{49}$ erg s$^{-1}$, and corresponding magnetic fields on the black hole of the order of $10^{12}$ Gauss - are astrophysically highly implausible. Combined with the relatively high random probability of coincidence of 0.22 percents, we conclude that the electromagnetic signal is likely unrelated to the BH merger.

1. Electromagnetic signals accompanying merger of compact objects

The report of the possible Fermi GBM signal (Connaughton et al. 2016) associated with the merger of two black holes detected by LIGO (GW150914, Abbott et al. 2016) could be a ground-breaking discovery in high energy astrophysics. The claimed event lasts approximately a second, produces non-thermal emission in the keV-MeV range with, most importantly, overall luminosity of $L_{EM} \sim 10^{49}$ erg s$^{-1}$. The event was not detected by INTEGRAL (Savchenko et al. 2016), which was covering the GW150914 region at the time of the GW trigger and has larger effective area above 100 keV.

The luminosity implied by the Fermi GBM detection exceeds by nearly 10 orders of magnitude the Eddington luminosity for a $M = 60 M_\odot$ star. Thus, the electromagnetic signal cannot be powered by a quasi-spherical accretion. An alternative possibility is that the accreting matter brings in the magnetic field that extracts rotational and/or translational energy of the central object(s). This process of electromagnetic extraction of mechanical energy, first proposed by Blandford & Znajek (1977) (see also Blandford (2002)) has many advantages in generating clean, highly relativistic outflow.

If the electromagnetic signal from GW150914 is real, it is then necessary that the emitting plasma is highly relativistic (by analogy with Gamma Ray Bursts (GRBs), e.g., Piran 2004). In our case the high compactness parameter at the source,

$$l_c = \frac{L_{EM} \sigma_T}{2 \pi G m_c M} = 1.5 \times 10^{13},$$

would require that the emission region propagates with the bulk Lorentz factor $\Gamma \approx 100$ - hence, a requirement of a clean, relativistic outflow (Lyutikov & Blandford 2003; Lyutikov 2006, discussed the electromagnetic model of GRBs). Below we concentrate on this more realistic scenario of the electromagnetic energy extraction from black hole(s); pressure and neutrino-driven outflows (e.g., Chen & Beloborodov 2007) would fare even worse at the expected low accretion rates.

The electromagnetic counterparts of mergers of compacts objects have been studied mostly for NS-NS binaries. These include the suggested association with short GRBs (e.g., Narayan et al. 1992), the precursor emission (e.g., Hansen & Lyutikov 2001), and the long lasting post-merger emission originating either from a supermassive magnetar (Metzger et al. 2011) or a black hole that keeps its magnetic “hair” - the magnetic flux (Lyutikov & McKinney 2011; Lyutikov 2013; Nathanail & Contopoulos 2014). In the case of BH-BH merger, the expected electromagnetic counterparts can be produced through accretion via Blandford-Znajek mechanism (Blandford & Znajek 1977, rotation of a black
hole in externally-supplied magnetic field), or through linear motion of black holes in magnetic field (Palenzuela et al. 2010b; Lyutikov 2011b), or a combination thereof (Morozova et al. 2014).

In all cases mentioned above, the electromagnetic power comes from the kinetic energy of the rotation or the linear motion of the central source, converted into Poynting flux with the “help” of the magnetic field (and subsequent dissipation and particle acceleration). Qualitatively, the electromagnetic power of relativistic outflows can be estimated as (Blandford & Znajek 1977; Blandford 2002)

\[ L_{EM} \approx \frac{V^2}{\mathcal{R}} \]  

(2)

where \( V \) is a typical values of the electric potential produced by the central engine and \( \mathcal{R} \approx 1/c \) is the impedance of free space.

For rotating objects, like neutron stars and black holes, this translates to

\[ L_{EM} \approx \Phi^2 \Omega^2 / c \]  

(3)

where \( \Phi \) is the open magnetic flux; for a neutron star \( \Phi_{NS} \approx B_{NS} R_{NS}^2 (R_{NS} \Omega_{NS}/c) \), while for a black hole (which has no closed field lines)

\[ \Phi_{BH} \approx B_{BH} R_{BH}^2 \]  

(4)

and

\[ \Omega_{BH} \approx \frac{a c}{R_{BH}} \]  

(5)

is the angular velocity of the black hole, \( a \) is the Kerr parameter (for detailed discussion see Tchekhovskoy et al. 2011).

Similarly, linear motion of a Schwarzschild black hole in external magnetic field with dimensionless velocity \( \beta \) produces luminosity (in this case \( V \approx \beta BR_{BH}, \) Lyutikov 2011b)

\[ L_{EM} = \frac{(GM)^2 B_0^2 \beta^2}{c^3} \]  

(6)

One of the major problem in applying the above relations to produce electromagnetic signal from merging black holes is that, generally, presence of plasma is required to anchor the magnetic field (the possibility that isolated black holes can keep magnetic field is an exception to this statement, see below). But very little plasma is expected to be present in the vicinity of black holes at the moment of the merger: like a kitchen blender the black holes clear of matter the inner few hundreds of Schwarzschild radii before the merger (Milosavljević & Phinney 2005; Farris et al. 2011). The magnetic field inside the cavity can still remain, created by the currents in the far-away accretion disk, but since at large distances the plasma densities are smaller, the expected magnetic field is also relatively small so that a weak electromagnetic signal is expected even for the merger of supermassive black holes (Lyutikov 2011b). Thus, little emission is expected instantaneous with the merger. Another possibility is that the recoil from the merger of black holes of unequal masses sends the final black hole slamming into the surrounding disk with a speed of few hundred to few thousand kilometers per second. This mechanism is expected to produce sub-Eddington luminosities (e.g., Lippai et al. 2008), too little to account for the observed signal.

One of the possible caveat (to the requirement of high circum-merger plasma density to contain the magnetic field) is the suggestion by Lyutikov & McKinney (2011); Lyutikov (2013) that black holes can keep the magnetic flux for times much longer than predicted by the no hair theorem. (This is due to the fact that the presence of highly conducting plasma around rotating black holes introduces a topological constraint that prohibits magnetic fields from sliding off the horizon - the no hair theorem (e.g., Price 1972; Misner et al. 1973) assumes that outside medium is vacuum.) Though the magnetic retention time is hard to calculate, it is unlikely that magnetic field can be kept on the black holes for cosmologically long times during the inspiral.
2. Application to possible electromagnetic counterpart of GW150914

The outflows powered by the rotational of the central source via the Blandford-Znajek type mechanism require the magnetic fields on the black hole of the order, Eqns. (3-5),

\[ B_{BH} \approx \frac{c^{3/2} \sqrt{L_{EM}}}{aGM} = 3 \times 10^{12} \text{G} \]  

for the inferred parameters of black hole of \( M \approx 60M_\odot \) and the Kerr parameter \( a \approx 0.7 \) (Abbott et al. 2016).

Similarly, the linear motion of black holes with the Keplerian velocity produces maximal electromagnetic power, see Eq. (6) with \( \beta \approx 1 \), of

\[ L_{EM, max} \approx \frac{(GM B_0)^2}{c^3} \]  

and requires

\[ B_0 \approx \frac{c^{3/2} \sqrt{L}}{GM} = 2 \times 10^{12} \text{G}. \]  

Both estimates (7) and (9) require exceptionally high magnetic fields, typical of young neutron stars and exceeding by many orders of magnitude the magnetic fields expected from accretion of the interstellar material. For example, regardless of the central mass, and parametrizing accretion luminosity required to contain magnetic fields (7-9) as

\[ L_{EM} = \eta \dot{M} c^2 \]  

(\( \eta \sim 0.1 \) is some efficiency factor), the required accretion rate is \( \dot{M} \approx 5 \times 10^{-5} M_\odot \text{ sec}^{-1} = 1.5 \times 10^3 M_\odot \text{ yr}^{-1} \). This is an unreasonably high accretion rate from the ISM or even in a binary system. Association of the BH merger with interiors of massive stars, that could possibly provide the required accretion rates (e.g., in a double collapsar-type scenario akin to MacFadyen & Woosley 1999), see Loeb (2016), contradicts the claimed \( \sim 1 \) second duration of the signal.

Collimation of the electromagnetic outflows, though reducing the overall energetics, is not likely to be important. First, the gravitation waves signal is only slightly anisotropic (The LIGO Scientific Collaboration & the Virgo Collaboration 2016). Highly anisotropic electromagnetic emission would make the contemporaneous detection highly unlikely, approximately by the ratio of the anisotropy solid angle over \( 4\pi \). Also, nozzle-type outflow collimation requires confinement (magnetic field can somewhat reduce the required confining pressure below the typical energy density in the jet, but cannot eliminate it completely). It is not expected that the circum-merger medium has sufficient density for confinement. Also note that isolated rotating black holes that retain magnetic field flux would produce equatorially-collimated outflows (Lyutikov & McKinney 2011; Nathaniil & Contopoulos 2014, edge-on orientation is slightly disfavored for GW150914, The LIGO Scientific Collaboration & the Virgo Collaboration (2016)). Linear motion of black holes in external magnetic field produces a dual pair of jets (Palenzuela et al. 2010b; Lyutikov 2011b).

Another possible subtlety is that the black holes’s orbital motion and/or the spin can amplify the external magnetic field in a way analogous to the two conducting spheres dynamo (Moffatt 1978; Blandford 1993). This possibility, likely, does not apply to the case of two orbiting/rotating black holes - black holes are, qualitatively, bad conductors (Thorne et al. 1986), so that the external magnetic field lines would slide along the spinning horizon (see, e.g., numerical calculations of Palenzuela et al. 2010a).

Finally, requiring that the magnetic field is produced by electric charge on one of the black holes (Zhang 2016) would imply a charge \( Q = GM \sqrt{L_{EM}/c^{3/2}} = 5 \times 10^{16} \) coulombs. This horrific amount of electric charge would have produced the electric field near the horizon \( E = \sqrt{L_{EM} c^{3/2}/(GM)} = 2 \times 10^{12} \) in cgs units (statvolts per centimeter), amounting to nearly 5% of the quantum Schwinger field \( E_Q = m_e^2 c^3/(\hbar e) \).
3. Conclusion

We discuss the physical requirements that the possible observation of the electromagnetic signal contemporaneous with GW150914 imposes on the circum-merger environment. We find that the required physical parameters at the source exceed by many orders of magnitude what is expected in realistic astrophysical scenarios. Given these constraints, and that the chance probability of the signal is not particularly low, and no signal was detected by other satellites, we conclude that the Fermi GBM signal contemporaneous with GW150914 is unrelated to the BH merger.

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