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POSSIBLE SHORT GAMMA-RAY BURSTS ASSOCIATED WITH BLACK HOLE - BLACK HOLE MERGERS

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ABSTRACT

The discovery of GW 150914 suggests that double black hole (BH-BH) mergers are common in the universe. If at least one of the two merging black holes carries a small amount of charge, the inspiral of the BH-BH system would drive a magnetic dipole normal to the orbital plane. A magnetosphere would be developed, and the system would behave like a giant pulsar with increasing wind power. If the BH charge can be as large as a factor of $\hat{q} \sim 10^{-15}$ of the critical charge Q_c of the BH, a detectable short-duration GRB would be generated right before the final coalescence. The GRB is supposed to have a short duration, nearly isotropic emission, and a delay with respect to the gravitational wave chirp signal. The putative short GRB coincident with GW 150914 detected with *Fermi* GBM can be interpreted with this model. The detections or non-detections of such GRBs associated with future BH-BH merger gravitational wave sources would lead to constraints on the charges carried by isolate black holes.

1. INTRODUCTION

Black holes (BHs) are uniquely described with three parameters, mass M, angular momentum J, and charge Q. Whereas the first two parameters have been measured with various observations for both stellar-mass and super-massive BHs, it has been widely believed that the Q parameter must be very small, since opposite charges tend to neutralize any possible net charges of a BH. However, no measurement of the value or upper limit of Q has been made for any BH.

Recently, the Laser Interferometer Gravitational-wave Observatory (LIGO) team announced the ground-breaking discovery of the first gravitational wave (GW) source, GW 150914, which is a BH-BH merger with two BH masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, respectively (Abbott et al. 2016a). The inferred event rate density of BH-BH mergers is high, i.e. $\sim (2-53)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Abbott et al. 2016b). Very intriguingly, the *Fermi* GBM team reported a 1-second long weak gamma-ray burst (GRB) 0.4 seconds after the GW event was detected (Connaughton et al. 2016). This is surprising, since unlike NS-NS and NS-BH mergers which can form a BH-torus system, and hence, may produce short GRBs (Paczýnski 1986; Eichler et al. 1989; Paczýnski 1991; Narayan et al. 1992; Mészáros & Rees 1992; Rezzolla et al. 2011), BH-BH mergers are not expected to have enough surrounding materials to power a short GRB via accretion.

Here I show that if at least one BH in the two merging BHs carries a small amount of charge, the inspiral of the BH-BH system would induce a giant magnetic dipole normal to the orbital plane. The "pulsar mechanism" would operate in the system, which would give rise to a potential short-duration GRB. A toy model is developed in §2. An interpretation to the GBM event is presented in §3. Some general discussion is presented in §4.

2. THE MODEL

A non-rotating, charged BH can be described by the Reissner-Nordström (RN) metric[1]:

$$ds^2 = \left(1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2}\right) c^2 dt^2 - \left(1 - \frac{r_s}{r} + \frac{r_Q^2}{r^2}\right)^{-1} dr^2 - r^2 (d\theta^2 + \sin^2\theta d\phi^2), \qquad (1)$$

where

$$r_s = \frac{2GM}{c^2}, \quad r_Q = \frac{\sqrt{G}Q}{c^2} \qquad (2)$$

are the Schwarzschild radius and the RN radius, respectively, M, Q are the mass and charge of the black hole, G and c are the gravitational constant and speed of light, respectively, and the electrostatic cgs units have been used. By equating r_s and r_Q, one may define a characteristic charge

$$Q_c \equiv 2\sqrt{G}M = (1.0 \times 10^{31}\ \mathrm{e.s.u.}) \left(\frac{M}{10 M_\odot}\right), \qquad (3)$$

which is $(3.3 \times 10^{21}\ \mathrm{C})\ (M/10M_\odot)$ in the S.I. units. The charge of this magnitude would significantly modify the space-time geometry with a magnitude similar to M. We consider a BH with charge

$$Q = \hat{q} Q_c, \qquad (4)$$

with the dimensionless parameter $\hat{q} \ll 1$. For simplicity, in the following we consider two identical BHs with the same M and Q.

As the two BHs revolve with the Keplerian speed[2], a circular current loop forms, which gives a magnetic dipole moment

$$\mu = \pi I r^2 = \sqrt{2GMr}Q = \frac{4\sqrt{2}G^{3/2}M^2}{c} \hat{q} \hat{r}^{1/2} = (1.3 \times 10^{33}\ \mathrm{G\ cm}^3) \left(\frac{M}{10 M_\odot}\right)^2 \hat{q}_{-15} \hat{r}^{1/2}, \qquad (5)$$

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[1] When spin is included, a more general metric is that of Kerr-Newmann. For the purpose of this *Letter*, the RN metric suffices.

[2] For an order-of-magnitude treatment, we apply classical mechanics and electromagnetism. A more precise treatment should consider general relativity correction.

where $I = 2Q/P$ is the current,

$$P = \frac{2\pi}{\sqrt{2GM}} r^{3/2} = 8\sqrt{2}\pi \frac{GM}{c^3} \hat{r}^{3/2} = (1.7 \text{ ms}) \left(\frac{M}{10M_\odot}\right) \hat{r}^{3/2} \quad (6)$$

is the Keplerian orbital period, and $r = \hat{r}(2r_s)$ is the separation between the two BHs, and $\hat{r}$ is the distance normalized to $2r_s$. Notice that $\hat{q}$ is normalized to 10^{-15}, suggesting that even a very small amount of charge can induce a large enough magnetic dipole for the observational purposes. For comparison, a magnetar with surface magnetic field $B_p \sim 10^{15}$ G has a magnetic dipole $\mu_{\rm mag} \sim B_p R^3 = (10^{33} \text{ G cm}^3) B_{p,15} R_6^3$.

This magnetic dipole aligns with the spin axis of the system. Unlike pulsars that have a perpendicular component of μ, such aligned rotators do not directly emit dipole radiation. In any case, unipolar induction due to the rapid rotation of the system would develop strong voltages across different field lines. Similar to pulsars, the curvature of the field lines and especially the general relativistic effect (Arons & Scharlemann 1979; Muslimov & Tsygan 1992; Harding & Muslimov 1998) would cause depletion of charge densities from the Goldreich-Julian density (Goldreich & Julian 1969) near the polar regions, leading to strong electric field parallel to the field lines ($E_\parallel$) in the so-called "gap" region. Background γ-ray photons entering the inner magnetosphere would be converted to e^+e^- pairs, which are accelerated in the opposite directions in the gap (Ruderman & Sutherland 1975). The accelerated charges emit γ-rays via curvature radiation, synchrotron radiation, and inverse Compton scattering, triggering a full pair-photon cascade (Zhang & Harding 2000). As a result, a magnetosphere is expected to be developed long time before the final coalescence, with a strong outflow or a magnetospheric wind launched (Usov 1994). The power of the wind is of the order of the dipole radiation power (Harding et al. 1999; Xu & Qiao 2001; Contopoulos & Spitkovsky 2006), i.e.

$$L_w \simeq \frac{2\mu^2\Omega^4}{3c^3} = \frac{c^7}{48G} \hat{q}^2 \hat{r}^{-5} \simeq (6.8 \times 10^{48} \text{ erg s}^{-1}) \hat{q}_{-15}^2 \hat{r}^{-5}. \quad (7)$$

Notice that this wind power does not depend on the BH mass M, and *is determined by fundamental constants and the dimensionless parameters* $\hat{q}$ *and* $\hat{r}$ *only*. A small amount of charge with $\hat{q} \sim 10^{-15}$ is adequate to make a transient with the power of a GRB.

The light cylinder radius of the magnetosphere $r_{\rm LC} = cP/2\pi$ rapidly shrinks with time. Also normalized to $2r_s$, one has

$$\hat{r}_{\rm LC} = \sqrt{2}\hat{r}^{3/2}, \quad \text{or} \quad \frac{\hat{r}_{\rm LC}}{\hat{r}} = \sqrt{2\hat{r}}. \quad (8)$$

At the final stage of coalescence ($\hat{r} \sim 1$), one has $\hat{r}_{\rm LC}/\hat{r} \sim \sqrt{2}$, suggesting a *nearly isotropic* outflow.

Another interesting behavior is that the power is very sensitive to $\hat{r}$, with the power increasing rapidly as the orbital separation shrinks. The highest power happens right before the final merger, so that it produces a *short-duration GRB*. One may estimate the time scale for the orbital separation to shrink from $\hat{r} = 2$ to $\hat{r} = 1$, during which L_w increases by a factor of 32. This is

$$t_{r,1} \lesssim \frac{P}{|\dot{P}|} = \frac{20}{3} \frac{GM}{c^3} \hat{r}^4 \simeq (5.2 \text{ ms}) \left(\frac{M}{10M_\odot}\right) \left(\frac{\hat{r}}{2}\right)^4, \quad (9)$$

where

$$\dot{P} = -\frac{192\pi}{5c^5} \left(\frac{2\pi G}{P}\right)^{5/3} f(e) \frac{M^2}{(2M)^{1/3}} \simeq \frac{6\sqrt{2}\pi}{5} \hat{r}^{-5/2} \quad (10)$$

is the orbital decay rate for GW radiation (Taylor & Weisberg 1989), with $f(e) \simeq 1$ for $e \simeq 0$ (which is the case before the final coalescence).

After the short, intense pulse of magnetosphere wind is launched, it travels to a distance before the emission is released. As a result, assuming that GW travels with speed of light, the γ-ray emission would be delayed with respect to the GW[3]. Suppose the GRB emission starts at radius R_1 with Lorentz factor Γ_1 and ends at radius R_2 with Lorentz factor Γ_2, one can define

$$t_1 = \frac{R_1}{2\Gamma_1^2 c}, \quad t_2 = \frac{R_2}{2\Gamma_2^2 c}. \quad (11)$$

Several observational time scales can be defined as follows:

- The delay time between the onset of the GRB and the final GW chirp signal is
$$t_{\rm GRB} \sim (t_1 - t_{r,1})(1+z). \quad (12)$$
- The rise time scale of the GRB is defined by
$$t_r \sim \max(t_{r,1}, t_2 - t_1)(1+z). \quad (13)$$
- The decay time scale of the GRB is defined by
$$t_d \sim t_2(1+z). \quad (14)$$
- The total duration of the GRB is
$$\tau = t_r + t_d. \quad (15)$$

3. GW 150914 AND THE POSSIBLE ASSOCIATED GRB

Connaughton et al. (2016) reported a weak, hard X-ray transient that was potentially associated with GW 150914. The false alarm probability is 0.0022, but the poorly-constrained localization is consistent with that of GW 150914. The putative GRB has a duration $\tau \sim 1$ s, and was delayed with respect to the GW signal by $t_{\rm GRB} \sim 0.4$ s. Assuming the redshift of GW 150914, $z = 0.09^{+0.03}_{-0.04}$ (Abbott et al. 2016a), the 1 keV - 10 MeV luminosity of the transient is $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1}.

Keeping in mind the high probability that this was a chance coincidence, we notice that the properties of the putative short GRB can be comfortably interpreted by the theory developed in §2. According to Eq.(7), the inferred luminosity immediately gives

$$\hat{q}_{-15} \simeq 1.6\eta_\gamma^{-1/2}, \quad (16)$$

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[3] The GW 150914 indeed leads the putative associated GRB by 0.4 s(Connaughton et al. 2016). This would give the tightest constraint on the Einstein's Equivalent Principle (EEP) to date (Wu et al. 2016).

where $\eta_\gamma = L_\gamma / L_w$ is the radiative efficiency of the GRB. If the short GRB / BH-BH merger associations are confirmed by future observations, this would be the first measurement of Q for any BHs in the universe.

The delay and the short duration of the GRB are also readily explained. According to Eq.(9), approximating $M \sim 30 M_\odot$ for both BHs in GW 150914, one may estimate $t_{r,1} \lesssim 15$ ms, which is $\ll$ the delay time $t_{\rm GRB} \sim 0.4$ s. One therefore has $t_{\rm GRB} \sim t_1$ (noticing $(1+z) \sim 1$), which gives a constraint on the onset radius of emission

$$R_1 \sim 2\Gamma_1^2 c t_{\rm GRB} \sim (2.4 \times 10^{14}~{\rm cm}) \left(\frac{\Gamma_1}{100}\right)^2. \qquad (17)$$

Even though the Lorentz factor Γ for such kind of GRBs is unknown, we can see that for nominal values ($\Gamma_1 \sim 100$) of known GRBs, this emission radius is much greater than the photosphere radius, suggesting that the GRB emission comes from an optically thin region. The large radius is consistent with the expectation of the models that invoke magnetic dissipation in a Poynting flux dominated outflow (e.g. Zhang & Yan 2011).

The weak signal does not allow a precise measurement of t_r and t_d. In any case, the pulse is asymmetric (Connaughton et al. 2016) with $t_d = t_2 \gg t_r = t_2 - t_1$, consistent with the theory. The total duration $\tau = 2t_2 - t_1 \sim t_2$. Taking the observed value $\tau \sim 1$ s, one can constrain the radius where emission ceases, i.e.

$$R_2 \gtrsim 2\Gamma_2^2 c\tau \sim (6.0 \times 10^{14}~{\rm cm}) \left(\frac{\Gamma_2}{100}\right)^2, \qquad (18)$$

where the $\gtrsim$ sign takes into account the fact that the true duration could be longer than the sensitivity-limited short duration 1 s.

A short GRB with such a luminosity has a faint afterglow. The non-detection of afterglow by the *Swift* team 2 days after the event (Evans et al. 2016) is consistent with this picture.

4. SUMMARY AND DISCUSSION

We have shown that for BH-BH mergers, if at least one of the BHs carry even a small amount of charge Q, the inspiral process generates a loop circuit, which induces a magnetic dipole. The system behaves like a giant pulsar with an increasing wind power. If $\hat{q}$ can be as large as 10^{-15}, the magnetospheric wind right before the coalescence would make a short-duration GRB. The GRB is expected to be delayed with respect to the GW chirp signal. We find that the putative short GRB signal associated with GW 150914 (Connaughton et al. 2016) can be well interpreted with this theory.

The nearly isotropic nature of this wind pulse suggests that every BH-BH merger could be associated with a short electromagnetic transient if Q is not strictly zero. The question is whether $\hat{q}$ can be large enough to make it observable. Given the large event rate of BH-BH mergers revealed by the detection of GW 150914 (Abbott et al. 2016b), the non-detection of very bright short GRBs already suggests that for the majority of BHs, $\hat{q}$ cannot significantly exceed 10^{-15}. This is consistent with the general expectation that BHs are essentially not charged.

Pessimistically, the weak short GRB signal detected by the *Fermi*/GBM team (Connaughton et al. 2016) is a chance coincidence and non-physical. If so, the upper limit of a signal would constrain $\hat{q}$ to be below 10^{-15}. Recalling that the L_w depends on fundamental constants and $\hat{q}$ only (Eq.(7)), the same constraint can be readily placed on all BH-BH merger systems in the future.

Optimistically, the GBM signal is real. One may then ask the question whether the same model may explain most, if not all, observed short GRBs to date. In view of a wide distribution of the short GRB luminosities (e.g. Sun et al. 2015), this model requires that $\hat{q}$ could be as large as 10^{-12} in some cases. In this model, however, no neutron-rich ejecta is available (in contrast to NS-NS and NS-BH mergers), so that no "kilonova" (or "macronova" or "mergernova", Li & Paczyński 1998; Metzger et al. 2010; Barnes & Kasen 2013; Yu et al. 2013; Metzger & Piro 2014) are expected. Those short GRBs with the claimed such associations (e.g. Tanvir et al. 2013; Berger et al. 2013; Yang et al. 2015; Gao et al. 2015) therefore demand NS-NS or NS-BH merger models. It may be possible that a sub-population of known short GRBs are due to BH-BH mergers. More joint GW-GRB observational campaigns and systematic archival data analyses are needed to test this possibility.

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