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Electromagnetic Luminosity of the Coalescence of Charged Black Hole Binaries

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The observation of a possible electromagnetic counterpart by the Fermi GBM group to the aLIGO detection of the merger of a black hole binary has spawned a number of ideas about its source. Furthermore, observations of fast radio bursts (FRBs) have similarly resulted in a range of new models that might endow black hole binaries with electromagnetic signatures. In this context, even the unlikely idea that astrophysical black holes may have significant charge is worth exploring, and here we present results from the simulation of weakly charged black holes as they orbit and merge. Our simulations suggest that a black hole binary with mass comparable to that observed in GW150914 could produce the level of electromagnetic luminosity observed by Fermi GBM (10^{49} ergs/s) with a non-dimensional charge of $q \equiv Q/M = 10^{-4}$ assuming good radiative efficiency. However even a charge such as this is difficult to imagine avoiding neutralization long enough for the binary to produce its electromagnetic counterpart, and so this value would likely serve simply as an upper bound. On the other hand, one can equivalently consider the black holes as having acquired a magnetic monopole charge that would be easy to maintain and would generate an identical electromagnetic signature as the electric charges. The observation of such a binary would have significant cosmological implications, not the least of which would be an explanation for the quantization of charge itself. We also study such a magnetically charged binary in the force-free regime and find it much more radiative, reducing even further the requirements to produce the counterpart.

I. INTRODUCTION

The exciting first direct detection of gravitational waves occurred recently [1], beginning the era of gravitational wave astronomy. Surprisingly, aLIGO's first detected event was not a binary neutron star merger as expected, but instead the merger of two quite massive black holes. Adding to the intrigue was a follow-up detection by the Fermi GBM team in the hard X-ray band that appears to be a coincident detection [2]. If indeed these X-rays came from aLIGO's stellar-mass (albeit large) binary black hole (BBH), new and possibly radical ideas are needed to explain how a BBH such as this would have produced such an electromagnetic signal.

The prospect that the first direct GW detection also resulted in a coincident detection is a great harbinger of what is to come from multi-messenger astronomy. However, significant skepticism surrounds this claim [3]. Fermi GBM faced a couple of obstacles for their follow-up: (i) The aLIGO trigger included a huge swath of sky (roughly 600 square degrees), and (ii) the detector (with a field of view of roughly 70% of the sky) only observed roughly 75% of the GW150914 skymap. The signal could meet the threshold for claiming a detection only in combination with aLIGO's detection. In particular, they find a signal 0.4s after the peak gravitational wave signal lasting for 1.0s. Two other detectors found no detection, including AGILE [4] and INTEGRAL [5]. We leave it to others to argue one way or another about coincidence, and propose here simply that possibilities such as this are worth exploring if only because future surprises are sure to continue.

In response, a number of scenarios in which a BBH could produce such an electromagnetic signature have

been proposed. These scenarios include: the collapse of a massive star into two clumps which subsequently collapse to black holes [6], the formation of a “dead” disk about one of the black holes that powers a burst during the pre-merger phase [7], the merger of two very massive, low metallicity stars [8], and the relativistic outflow of material into an ambient medium [9]. A critical examination of aspects of some of these models is presented in Ref. [10].

A proposal by Zhang [11] (see also a related proposal by Ref. [12]) argues that a charged BBH could have produced the signal. The motion of a charged black hole constitutes a current loop that drives the resulting Poynting flux. This flux interacts with the surrounding environment which introduces a time lag corresponding to the 0.4s observed by Fermi GBM. Although the charge required to produce the observed energy flux is small in non-dimensional units, the charge in absolute terms is still 5×10^{16} C. In any case, one does not expect to find astronomical objects with a net charge for long times because of the huge electromagnetic forces trying to neutralize such objects.

Regardless of the status of this Fermi GBM detection, the observations of fast radio bursts (FRBs) similarly require new ideas about possible electromagnetic signals. Such bursts are extra-galactic, radio transients with durations of just a few milliseconds [13]. Although one reported FRB repeats [14, 15] and hence cannot be explained by cataclysmic events, a sub-class of FRBs may still be explainable by binary mergers [13] (also see Ref. [16]). For example, Ref. [17] proposes the discharging of charged black holes as a source of FRBs.

And although a proposal such as this naturally merits much skepticism, we study this scenario both because the

possible coincident detection calls for unexpected ideas and because the dynamics of charged black holes are interesting in their own right (having been studied in the head-on collision case, for example, by Refs. [18–20]). Indeed, it makes sense to explore a variety of implications of this detection if only to set bounds on black hole charge [21, 22].

Another motivation arises from studies of the interaction of black holes with an external magnetic field that showed a significant Poynting flux powered by the kinetic energy of the black holes. This coupling is the generalization of the Blandford-Znajek effect for rotating black holes and it is quite a robust effect [23, 24]. However, because black holes generally do not support their own magnetic field, such studies usually assume an external source of the field such as a circumbinary disk. However, a black hole can support a monopolar electric or magnetic charge, and so this work is a natural extension of such studies (and these studies also motivate the magnetic reconnection model of Ref. [12] within a charged BBH scenario).

Despite the natural skepticism about astrophysical charged black holes, a number of proposals explain how a black hole might maintain a charge. Ref. [25] (in particular see Ch. 11) describes that certain stable structures can shield a BH from electric discharge, such as a ring of charged particles (i.e., with charge opposite that of the black hole) rotating at a certain radius. Another argument begins with a BH rotating with angular momentum J immersed in an external magnetic field of strength B_0 . Such a BH will become charged up to $Q = 2B_0J$ so that with the Kerr limit, $Q/M \leq 2B_0M$ [26]. If somehow a black hole binary found itself within a very strong magnetic field supported by a circumbinary disk, the charge could similarly be significant. There is also the possibility that a star becomes charged prior to collapse to a black hole and it maintains the charge during the collapse (see Ref. [27] and references therein). It should be said that these scenarios generally apply for extremely small charges.

Some models of dark matter incorporate a dark electromagnetism that could potentially result in charged BHs [28, 29]. To be relevant to the Fermi GBM detection, the dark Poynting flux would somehow have to convert into hard (non-dark) X-rays.

Finally, black holes may accrete cosmological magnetic monopoles [30, 31]. In the region outside such magnetically charged black holes, the symmetry between electric and magnetic fields in the absence of charges and currents (outside the event horizons), would imply that their dynamics would be identical to a charged BBH binary. While monopoles have the advantage that their charge would not be quickly neutralized, their realism is questioned by never having been observed. However, they are thought to be formed in the early universe via symmetry breaking in a wide range of field theories.

In this paper, we study the merger of two black holes initially in quasi-circular orbits with very weak charges

that do not affect the metric. We analyze the gravitational and electromagnetic wave production and comment on the model by Zhang [11].

II. NUMERICAL SETUP

To model the merger of two charged black holes, we use our long standing code that incorporates fully non-linear general relativity coupled to an electromagnetic field. However, even within this framework, the model is not complete until the particular environment outside the black holes is specified. If the magnetosphere is filled with a tenuous plasma, one could assume that magnetic forces dominate over inertial forces, so that currents are generated to cancel the Lorentz forces (i.e., the force-free approximation). Such a condition cannot hold near the electrically charged black holes however, and instead perhaps the “charge starved” environment (see Ref. [25]) resembling electrovacuum is more appropriate here. And so we consider first electrically charged black holes in electrovacuum (or equivalently black holes with magnetic charges), and then consider magnetically charged black holes within a force-free environment in the subsequent section.

Therefore, we solve the Einstein-Maxwell equations to model the electromagnetic field and the strong gravity dynamics in the current scenario of binary charged black holes. We use the BSSN formulation [32, 33] to implement the Einstein equations, and to implement the Maxwell equations we use the formulation described in Refs. [34, 35]. We have employed this formulation to study other electrovacuum scenarios involving black holes [35–37].

We consider a binary of charged black holes described by individual masses m_i and charges Q_i . It is convenient to use a non-dimensional quantity for the charge $q_i = Q_i/m_i$. In this first work we restrict ourselves to non-spinning cases ($a_i = 0$) and small values of q , so that the energy associated with the electromagnetic field remains several orders of magnitude smaller than that of the gravitational field. The electromagnetic field therefore has a negligible influence on the dynamics of the black holes, and its feedback on the spacetime is not included in our simulations. Notice that, for small values of q , the electromagnetic luminosity should scale with q^2 . The force-free system, as it involves magnetic reconnection and current sheets, is nonlinear and so this scaling is not exact. Nevertheless, the luminosities and energies are sufficiently coarse-grained that we find the scaling holds quite well. For the cases in which both black holes are charged, we study only those with equal charge magnitudes.

We adopt initial data corresponding to quasi-equilibrium, equal-mass, non-spinning black holes with $q = 0.01$ initially separated by a distance of $\approx 8M$. With this separation, the merger takes place after about 4–5 orbits. The initial data for the metric is constructed by

superposing two boosted, uncharged black holes. The electromagnetic field is initialized as a superposition of the fields of a boosted isolated charge for each BH. Notice that while the electromagnetic constraints are satisfied by the initial data, the Hamiltonian and momentum constraints are only approximately satisfied by this construction. To explore the large charge regime, one would need to solve the full initial data problem by solving the full set of elliptic constraint equations.

To extract physical information, we monitor the Newman-Penrose radiative scalars; in particular, the electromagnetic (Φ_2) and gravitational (Ψ_4) radiative scalars. These scalars are computed by contracting the Maxwell and the Weyl tensors respectively with a suitably defined null tetrad

$$\Phi_2 = F_{ab}n^a\bar{m}^b, \quad \Psi_4 = C_{abcd}n^a\bar{m}^b n^c\bar{m}^d, \quad (1)$$

and they account for the energy carried off by outgoing waves at infinity. The total energy flux (luminosity) in both electromagnetic and gravitational waves are

$$L_{\text{EM}} = \lim_{r \rightarrow \infty} \int \frac{r^2}{2\pi} |\phi_2|^2 d\Omega, \quad (2)$$

$$L_{\text{GW}} = \lim_{r \rightarrow \infty} \int \frac{r^2}{16\pi} \left| \int_{-\infty}^t \Psi_4 dt' \right|^2 d\Omega. \quad (3)$$

In order to estimate the collimation as a function of time, we compute the luminosity, L_θ , within a jet opening angle θ with respect to the perpendicular to the orbital plane. This luminosity is normalized with respect to the luminosity over the hemisphere, L_{90° , so that for perfectly collimated emission (i.e. within the opening angle θ) this normalized quantity, L_θ/L_{90° , is just unity.

We adopt finite difference techniques on a regular Cartesian grid to solve the overall system numerically. To ensure sufficient resolution in an efficient manner we employ adaptive mesh refinement (AMR) via the HAD computational infrastructure that provides distributed, Berger-Oliger style AMR [38, 39] with full sub-cycling in time, together with an improved treatment of artificial boundaries [40]. A fourth order accurate spatial discretization satisfying a summation by parts rule together with a third order accurate in time Runge-Kutta integration scheme are used to help ensure stability of the numerical implementation [41]. We adopt a Courant parameter of $\lambda = 0.25$ so that $\Delta t_l = 0.25\Delta x_l$ on each refinement level l . On each level, one has full sub-cycling in time and therefore one ensures that the Courant-Friedrichs-Levy (CFL) condition dictated by the principal part of the equations is satisfied. Our evolutions generally adopt seven levels of refinement with a finest resolution of $\Delta x^i = 0.04M$. We use a self-shadow method as our refinement criterion, although the truncation error is dominated mainly by the spacetime quantities. Because, as mentioned, this code has been used extensively for a number of other projects, it has already been rigorously tested. We also test for convergence, charge conservation, and divergencelessness of the magnetic field (outside the

black hole horizons) here. We use geometric units in which $G = c = 1$ unless otherwise stated.

III. RESULTS

Because we study the binary in the weakly charged limit, the dynamics of the binary are independent of initial charge configuration. The binary orbits for 4-5 cycles before merging into a single spinning black hole as shown in Fig. 1. We have labeled the times such that $t = 0$ occurs when the gravitational wave luminosity peaks (as shown in Fig. 3).

A simple calculation indicates that the gravitational wave radiation, at the lowest order, has a quadrupolar structure [42]. For equal mass binaries, the luminosity carried away by these waves goes as $L_{\text{GW}} \propto (M\omega)^{10/3}$, where we have used the Keplerian relation $\omega^2 r^3 = M$.

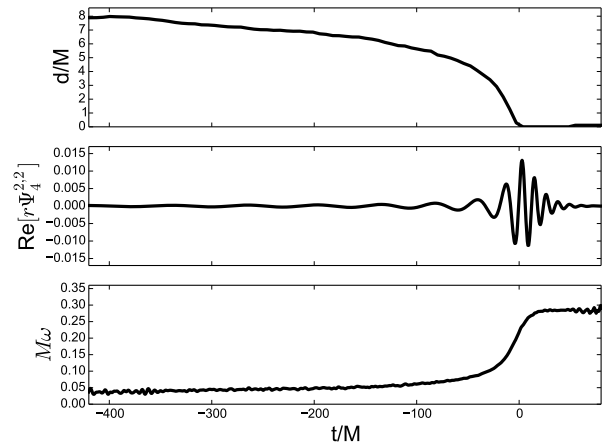


FIG. 1: The dynamics of the binary system and its gravitational radiation. **Top:** The separation, d , as a function of time, obtained by the coordinate distance between the two minima of the conformal factor χ . **Middle:** The real part of the $l = m = 2$ mode of the Newman-Penrose scalar Ψ_4 . **Bottom:** The angular frequency of the binary obtained from the main gravitational-wave mode.

A. Electrovacuum environment

We consider three different charge configurations $\{+, +\}$, $\{+, 0\}$ and $\{+, -\}$ and focus on the electromagnetic luminosity of each case. Notice that although in this section we consider black holes with electric charge, these results apply to magnetically charged black holes as well. The $\{+, +\}$ binary consists of two positively charged black holes that ultimately merge into a single, charged, spinning (Kerr-Newman) black hole (see the electric field configuration in Fig. 2). The $\{+, -\}$ binary consists of black holes with opposite charge and thus no net charge. The $\{+, 0\}$ binary has one uncharged black

hole and represents a superposition of the other two configurations.

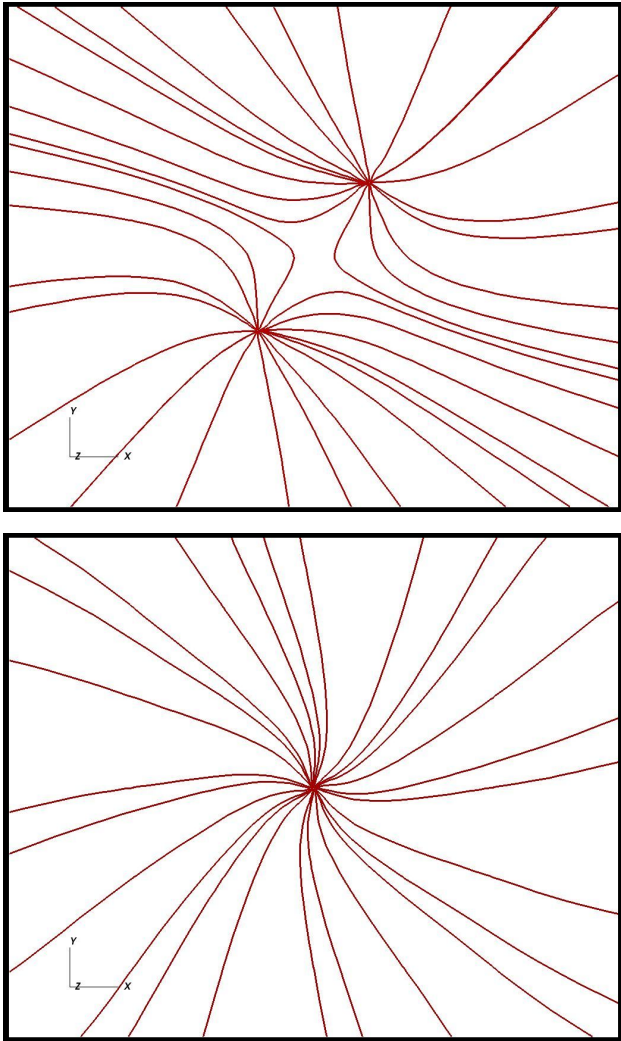


FIG. 2: The electric field in the equatorial plane, $z = 0$, for the *electrovacuum* case. Only a centered region of the computational domain is shown, spanning a width of four times the initial separation. **Top:** Before and **Bottom:** after the merger of the BBH system with $\{+, +\}$ charge configuration. After the merger, the electric field quickly settles to that of a spinning charge. The black holes are located where the field lines converge.

The electromagnetic luminosity is generally dominated by the dipolar radiation so that for a system of two orbiting charges the luminosity scales as $L_{\text{EM}}^{\text{dip}} \propto q^2(M\omega)^{8/3}$. If no dipole is present, the next dominant term for an orbiting pair of charges is the quadrupolar contribution $L_{\text{EM}}^{\text{quad}} \propto q^2(M\omega)^{10/3}$.

We display the electromagnetic luminosity for each case in Fig. 3. The most radiative case is $\{+, -\}$, followed by the $\{+, 0\}$ case, and finally the $\{+, +\}$. The high luminosity of the $\{+, -\}$ case can be understood in terms of its dipole moment. The most radiative electromagnetic radiative mode arises from the acceleration of

the dipole moment, which will produce dipolar radiation corresponding to the $l = m = 1$ mode. The $\{+, +\}$ case has no dipole moment by symmetry, and the $\{+, 0\}$ case has half the dipole moment of the $\{+, -\}$ case. Instead, the $\{+, +\}$ binary radiates quadrupolar radiation giving it the same frequency dependence as the gravitational wave radiation. The case $\{+, 0\}$ has both dipolar and quadrupolar contributions, although the dipolar is dominant. The differences among the modes for the different configurations are shown in Fig. 5. The $\{+, +\}$ case emits radiation mainly near the equatorial plane while the $\{+, -\}$ case radiates more isotropically.

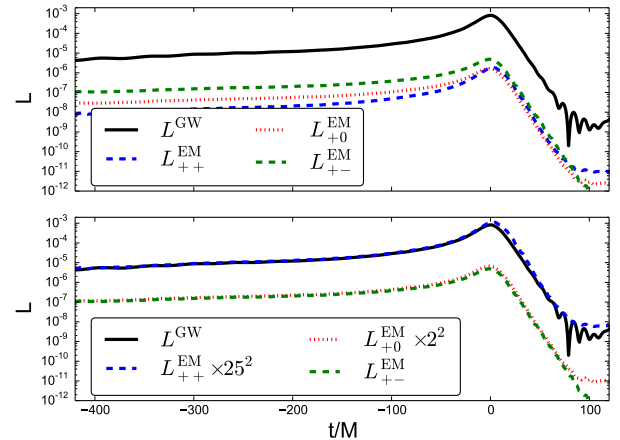


FIG. 3: Electromagnetic and gravitational luminosities for the different *electrovacuum* configurations. **Top:** The gravitational luminosity (solid black) is the same among all cases. The electromagnetic luminosities vary for the different charge configurations. **Bottom:** The $\{+, +\}$ EM luminosity has been rescaled to show that the electromagnetic luminosity is proportional to the gravitational luminosity. Likewise, the $\{+, 0\}$ EM luminosity has been rescaled showing that it is roughly a quarter of the luminosity of the $\{+, -\}$ case.

We display the luminosities in terms of the angular frequency of the binary in Fig. 4. We also fit these luminosities at early times before the last part of the coalescence of form $a\omega^b$ for real constants a and b , obtaining

$$L_{++} = 1.3 \times 10^{-8} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{10/3} \quad (4)$$

$$L_{+0} = 3.8 \times 10^{-8} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{8/3} \quad (5)$$

$$L_{+-} = 1.3 \times 10^{-7} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{8/3} \quad (6)$$

in good agreement with the expected analytic estimates. Notice however that the luminosities deviate from the fits at frequencies higher than $M\omega = 0.12$ (i.e., separations smaller than $d = 4M$), when the system departs from a slow inspiral and relativistic effects becomes more predominant.

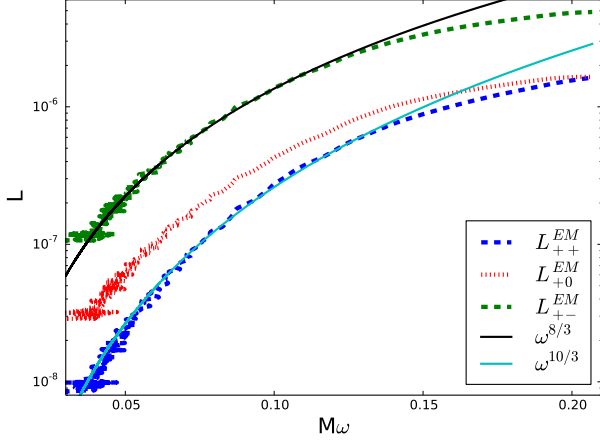


FIG. 4: Electromagnetic luminosities as a function of the angular frequency of the binary for the *electrovacuum* cases. Fits of these luminosities to a power law in the frequency are also shown (solid curves). Notice that the dependence of the luminosities on the orbital frequency follows that expected from a pair of orbiting charges, at least up to the plunge.

Integration of the luminosities in time gives estimates of the total radiated energies

$$E_{\text{GW}}/M = 3 \times 10^{-2}, \quad E_{\text{EM}}/M \approx 10^{-4} \left[\frac{q}{0.01} \right]^2 \quad (7)$$

where the coefficients for the electromagnetic energies range over $\{7.6 \times 10^{-5}, 8.6 \times 10^{-5}, 2.7 \times 10^{-4}\}$ for the $\{++, +0, +-\}$ configurations.

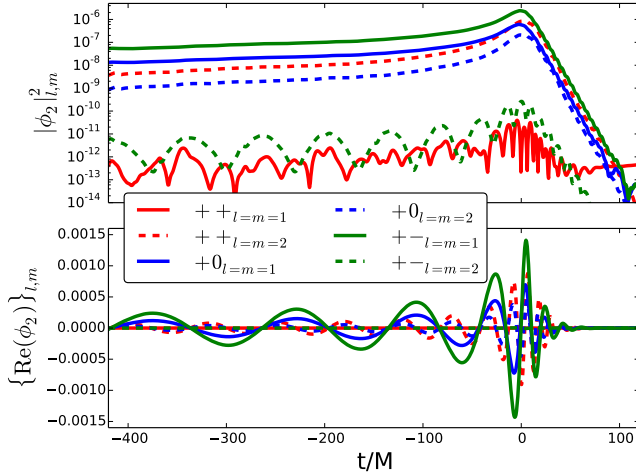


FIG. 5: The main spin-weighted spherical-harmonic modes of the Newman-Penrose scalar Φ_2 describing the electromagnetic radiation for the different *electrovacuum* configurations. **Top:** The norms of the main modes. **Bottom:** The real part of the main modes.

B. Force-free environment

We consider now magnetically charged black holes immersed in a magnetically dominated, low density plasma such that the Lorentz force vanishes, leading to the force-free approximation [43, 44]. Such a regime excludes electrically charged black holes, and so we will only consider the binaries with a magnetic monopole charge.

We evolve the same configurations as in the electrovacuum case and display the electromagnetic luminosities in Fig. 6. Once again, the luminosity is still dominated generally by the dipolar radiation. The most radiative case is now the $\{+, +\}$, followed by the $\{+, 0\}$ case, and finally the $\{+, -\}$. Note that in contrast to the electrovacuum case, the force-free evolutions tend to be less smooth having to resolve magnetic reconnection and current sheets, particular with the $\{+, -\}$ case.

In addition, the luminosity of the $\{+, -\}$ case is quite collimated during the inspiral and merger (the collimations are displayed in Fig. 7). In contrast, the $\{+, +\}$ luminosity is not as collimated during the inspiral, but its collimation increases towards the merger. The post-merger collimation is consistent with the Blandford-Znajek emission from a spinning black hole with a magnetic monopole. The collimation of the $\{+, 0\}$ case is the smallest during the inspiral and increases only during the merger when the remnant spinning black hole is formed, again consistent with the emission through the Blandford-Znajek mechanism.

This behavior, completely opposite to the electrovacuum case, can be understood by analyzing the mode decomposition of ϕ_2 (shown in the bottom panel of Fig. 6). The strongest electromagnetic mode in the $\{+, +\}$ configuration corresponds to the $l = 1, m = 0$, followed by the $l = m = 2$. The magnetic field structure of the late inspiral stage reveals that the binary resembles a single spinning black hole in a force-free environment. Previous studies of spinning black holes have shown that for fairly generic magnetic field topologies, such a configuration radiates axisymmetrically with a $m = 0$ mode [44]. That the binary is not axisymmetric means that there is an additional, sub-dominant component, namely the $l = m = 2$ mode.

Another way of interpreting the results during the inspiral phase is by considering the motion of one of the black holes. This motion, relative to the other BH, will produce deformations of the magnetic field, and, in a force-free environment, these perturbations will propagate along the magnetic field lines as Alfvén waves, carrying away energy from the system. These waves will be stronger where the magnetic field lines and the black hole velocity are perpendicular to each other. In particular, the radiation will be more efficient along the polar caps where the magnetic fields are not strongly affected by the interaction with the other charged black hole. The high degree of collimation of the radiation in the $\{+, +\}$ case supports this interpretation.

The $\{+, -\}$ case is very different, since the magnetic

field lines from one black hole reconnect with the magnetic field lines from the other one, forming a dipole rotating in the equatorial plane. Perturbations of the magnetic field travel from one black hole to the other, but only the open magnetic field lines can transport outgoing radiation. Thus, the luminosity—which is dominated by the $l = m = 1$ mode—is reduced compared to the $\{+, +\}$ configuration, and tends to zero after the merger when the charges neutralize.

The $\{+, 0\}$ case is not a clean superposition of the other two cases as appeared in the electrovacuum case because the force-free equations are nonlinear. The single most luminous modes of the other two force-free cases appear as the two most significant modes for this case, namely the dipolar radiation mode ($l = m = 1$) and the axisymmetric $l = 1, m = 0$ mode. One can understand this by considering the uncharged black hole as it moves through the magnetic field sourced by the charged BH. As in the electrovacuum case, its motion induces an electric charge separation on the uncharged BH horizon, but, unlike the electrovacuum case, the force free environment dictates the interaction of the fields of the two black holes. Interestingly, the total luminosity prior to merger is quite similar to that of the corresponding electrovacuum case.

Note that the three configurations differ significantly in how luminous they are as well as how collimated they are because of the interaction between the black holes. If somehow future electromagnetic counterparts lend support to this scenario, perhaps the charge configuration of the binary can be extracted from these features.

The disparate behavior of the post-merger luminosities (top panel of Fig. 6) are straight forward to explain. In particular, both the $\{+, +\}$ and the $\{+, 0\}$ cases produce spinning BHs with magnetic charge in a force-free environment. This solution should correspond precisely to the well-known stationary, radiating solution found by Blandford and Znajek with a monopole magnetic field [44]. That the $l = 1, m = 0$ mode plateaus while the other modes quickly turn off is consistent with the post-merger solution approaching the Blandford-Znajek solution (see the bottom panel of Fig. 6). In contrast, the $\{+, -\}$ produces an uncharged black hole and so the luminosity simply shuts off.

We display the luminosities in terms of the angular frequency of the binary in Fig. 8. We again fit these luminosities at early times before the last part of the coalescence, obtaining

$$L_{++} = 1.7 \times 10^{-6} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{1.6} \quad (8)$$

$$L_{+0} = 4 \times 10^{-8} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{3.1} \quad (9)$$

$$L_{+-} = 3 \times 10^{-7} \left[\frac{q}{0.01} \right]^2 \left[\frac{M\omega}{0.04} \right]^{1.9} \quad (10)$$

Although there are no analytic estimates to compare with these results, it is reasonable to consider a similar force-

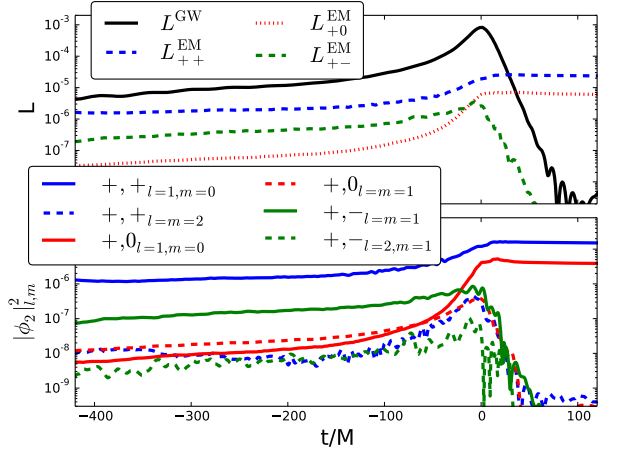


FIG. 6: Electromagnetic and gravitational luminosities from the different cases in a *force-free environment*. **Top:** The gravitational luminosity (solid black) is shown for comparison with the previous electrovacuum cases. The electromagnetic luminosities vary for the different charge configurations. **Bottom:** The norms of the main spin-weighted spherical-harmonic modes of the Newman-Penrose scalar Φ_2 , showing that the radiation is mainly dipolar.

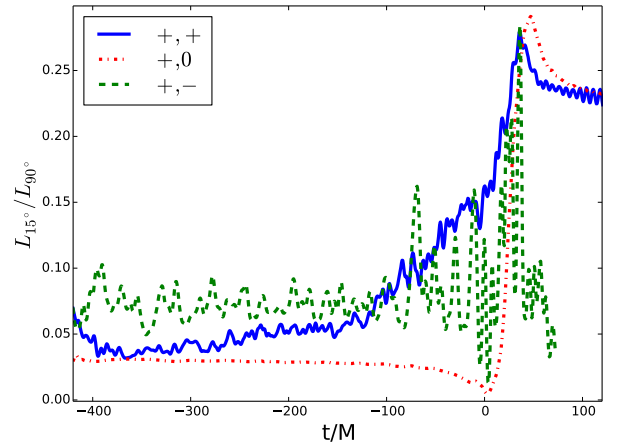


FIG. 7: The normalized luminosities emitted in a jet opening angle of 15° (which estimates the collimation of the radiation) for the *force-free* cases. The $\{+, -\}$ case is quite collimated during the inspiral and merger. In contrast, the collimation of the other two cases increases towards the merger as would be expected from a spinning black hole with magnetic monopole charge through the Blandford-Znajek mechanism.

free scenario given by a binary black hole immersed in an external magnetic field. Numerical simulations for such a system yield a dependence $L \propto \omega^{5/3-6/3}$ [45], which is a range consistent with our results, albeit with a different magnetic field topology.

Finally, integration of the luminosities in time gives estimates of the total radiated energies an order of mag-

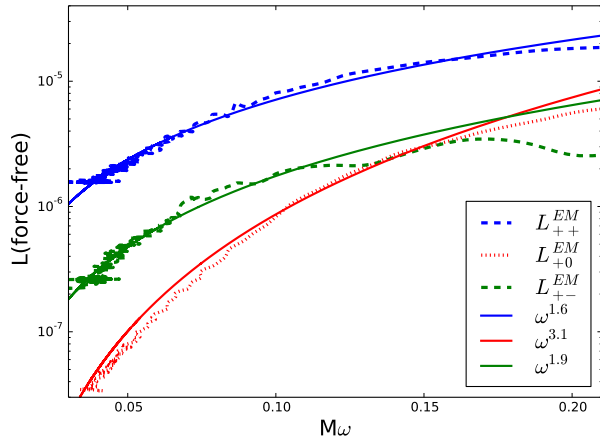


FIG. 8: Electromagnetic luminosities of the *force-free* cases as a function of the angular frequency of the binary. Fits of these luminosities to a power law in the frequency are also shown (solid curves).

nitude larger than the electrovacuum case, namely

$$E_{\text{EM}}/M \approx 10^{-3} \left[\frac{q}{0.01} \right]^2 \quad (11)$$

where the coefficients for the electromagnetic energies range over $\{5 \times 10^{-4}, 6 \times 10^{-4}, 5 \times 10^{-3}\}$ for the $\{++, +0, +-\}$ configurations.

IV. DISCUSSION

Because our primary interest in this study is to constrain the presumed charge of the binary detected by GW150914, we introduce a mass of $M \approx 65M_{\odot}$ and find an estimate of the peak electromagnetic luminosity and total energy during the coalescence of

$$L_{\text{EM}}^{\text{peak}} \approx 10^{53} \text{ ergs/s} \left[\frac{q}{0.01} \right]^2 \quad (12)$$

$$E_{\text{EM}} \approx 10^{50} \text{ ergs} \left[\frac{q}{0.01} \right]^2 \left[\frac{M}{M_{\odot}} \right]. \quad (13)$$

Therefore, if the Fermi GBM detection of 10^{49} ergs/s is indeed coincident with GW150914, then our results suggest that $q \approx 10^{-4}$ if the reason the binary was observable as a weak sGRB is because of its charge. These results are mostly consistent with the estimates of Zhang [11]. It should also be noted that one generally expects that the electromagnetic energy we measure here will couple to the environment surrounding the merger, ultimately producing the photons seen on Earth. This process will introduce a delay between the gravitational and electromagnetic signals as discussed by Zhang [11]. Here, we are assuming the efficiency of this process is quite high.

For such a binary to be the engine behind a (non-repeating) FRB with luminosity of 10^{43} ergs/s, the charge

could be significantly less, roughly $q \approx 10^{-10}$. Of course, we are only considering energies and luminosities here because the astrophysics of how this electromagnetic energy gets processed into observable radiation is extremely difficult. And so we acknowledge that hard X-rays and radio are very different bands and the details of how such signals would be created would vary considerably.

As we acknowledge in the introduction, there is well deserved skepticism about that a BBH could maintain its charge, even a charge of $q = 10^{-4}$, until merger. Another possibility is that one can switch the roles of electric and magnetic fields to consider a binary with at least one magnetic monopole charge. Magnetic monopoles are widely thought to be created in the early universe, and cosmological models generally have to explain why no monopoles have been observed. Inflation severely dilutes the density of monopoles while some models assert that primordial black holes might have accreted them [30].

Recent work suggests that a small window in black hole mass is allowed by various constraints for primordial black holes to be a primary source of dark matter and it happens that GW150914 fell in that window [46–48]. However, Ref. [46] does not consider the effects of any magnetic field on the cosmological dynamics, and so the viability of a magnetically charged, primordial black hole binary forming, surviving, and ultimately merging in the GW150914 event is by no means trivial. Furthermore, such a binary would also have implications for the primordial magnetic field [49].

Perhaps GW150914 contains at least one such monopole that accounts for the electromagnetic counterpart. If so, then with $q = 10^{-4}$, its surface magnetic field would be approximately 10^{14} G providing appropriate conditions similar to those thought to power short gamma ray bursts from binary neutron star mergers. Our studies of the BBH within a force-free environment showed even higher luminosities than the electrovacuum cases, although the $\{+, +\}$ may be excluded both because it may produce a long-lived post-merger signal (that was not observed) and because its signal appears highly collimated and not likely to be observed in the first place.

Unlike the electrically charged case, it would be difficult to neutralize any magnetic charge of the black holes. And because nothing rules out the existence of magnetic monopoles, perhaps the strongest argument against such a scenario is simply that no one has seen one before. However, no one had seen a $30M_{\odot}$ black hole before, and so maybe with GW150914, we have now seen both.

Although no counterparts to GW151226, aLIGO’s most recent detection [50], were found by Fermi GBM [51], we look forward to an exciting era of both gravitational wave astronomy and its accompanying multi-messenger counterparts.

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