Binary Black Holes' Effects on Electromagnetic Fields

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In addition to producing gravitational waves, the dynamics of a binary black hole system could induce emission of electromagnetic radiation by affecting the behavior of plasmas and electromagnetic fields in their vicinity. We here study how the electromagnetic fields are affected by a pair of orbiting black holes through the merger. In particular, we show how the binary's dynamics induce a variability in possible electromagnetically induced emissions as well as a possible enhancement of electromagnetic fields during the late-merge and merger epochs. These time dependent features will likely leave their imprint in processes generating detectable emissions and can be exploited in the detection of electromagnetic counterparts of gravitational waves.

Introduction.—As the era approaches when the detection and analysis of gravitational waves joins electromagnetic observations, studying a number of astrophysical systems in both wavebands becomes an exciting prospect. Indeed, most astrophysical systems which produce gravitational waves are very likely also electromagnetically bright (see, e.g., [1,2]), with the exception of systems composed solely of black holes.

One example of such a system is a black hole surrounded by an accretion disk. This scenario has been used to explain a vast range of spectacular phenomena, from active galactic nuclei (AGNs) and quasars to gamma ray bursts, all of which are prodigious emitters of electromagnetic energy. Strong emission from these systems is understood as the result of radiative processes within jets powered by the extraction of rotational and binding energy.

The pioneering work of Penrose [3] and Blandford and Znajeck [4], together with a large body of subsequent work, has provided a basic understanding of possible mechanisms to explain highly energetic emissions from single black hole systems interacting with surrounding plasmas. The interaction of electromagnetic field lines with the strong gravitational field of a rotating black hole is the fundamental component of these mechanisms to explain the acceleration of particles that traverse the black hole's ergosphere. The scenario of a pseudostationary, single black hole interacting with an accretion disk is reasonably well understood, and this system is employed to explain energetic phenomena such as gamma ray bursts, AGNs, quasars, blazars, etc. However, a highly dynamical stage may occur prior to such a pseudostationary regime which could give rise to strong emissions.

A related system, studied here, involves the collision of supermassive black holes, whose gravitational radiation would be detectable by the laser interferometric space antenna (LISA). To date, strong observational evidence indicates that massive black holes exist in the centers of most galaxies, and that galaxies have undergone mergers in their past. In galactic collisions, the initial black holes eventually merge as their orbits shrink through a variety of mechanisms. As discussed in [5–7], a circumbinary disk is formed as the binary hollows out the surrounding gas (see, e.g., [8–10]). As the distance between the black holes decreases, the dynamics of the binary become governed by the emission of gravitational waves and disconnected from the properties of the disk [11,12].

While the late time dynamics of the system can be understood in terms of the pseudostationary picture mentioned above, an interesting intermediate regime would include magnetic fields, anchored at the circumbinary disk, being influenced by the orbiting behavior of the two black holes. In particular, both precursor emission and enhancement of electromagnetic energy could be possible as the electromagnetic fields interact with the gas being stirred and compressed by the black holes' shrinking orbit. Consequently, the late premerger and merger dynamics of a supermassive binary black hole system could have a strong influence on the possible interaction between the remaining gas and the electromagnetic fields and even seed several emission mechanisms more strongly. In this work we study such a scenario by considering the Einstein-Maxwell system in a setup that describes a pair of black holes close to the merger epoch, and we examine the electromagnetic field behavior and compare to the single black hole case. While we do not consider a plasma in our current study, our analysis helps us to understand the possible behavior in its presence and lay the foundations to future work in this direction.

Overview of the numerical approach.—We solve the coupled Einstein-Maxwell system to model the black hole merger interacting with an externally sourced magnetic field. The Einstein equations are written in the generalized harmonic formalism described in [13]. The Maxwell equations are written directly in terms of the electric and magnetic fields, as in [14]. The electromagnetic fields have astrophysically motivated magnitudes, and thus their energy is several orders of magnitude smaller than the gravitational field energy. Hence the dynamical effects of the electromagnetic fields on the geometry are negligible. This fact is corroborated by simulations not displaying any difference in the black holes dynamics with an initial magnetic field an order of magnitude larger and even zero, than the one employed here.

In both systems of equations, the constraints are kept under control via damping mechanisms: constraint damping for the Einstein equations [15] and divergence cleaning for the Maxwell equations (similar to that defined in [16] for ideal MHD). A combination of Sommerfeld and constraint preserving boundary conditions are applied at the outer boundary [17] for both systems. The incoming modes of the electromagnetic fields are defined via Dirichlet (maximally dissipative) conditions induced from the physical picture of a circumbinary disk present beyond the computational domain.

We use the HAD computational infrastructure that provides distributed Berger-Oliger style adaptive mesh refinement (AMR) [18,19] with full subcycling in time, together with a novel treatment of artificial boundaries [20]. The refinement regions are determined using truncation error estimation via a shadow hierarchy. A fourth order spatial discretization satisfying a summation by parts rule together with a third order Runge-Kutta scheme for the time integration are used to help ensure stability of the numerical implementation [21].

Overview of the physical setup.—To explore the effects of the merger dynamics on the electromagnetic field, we compare certain cases of a single spinning black hole with cases of merging holes. In all cases, the orbital plane of the evolution (or equatorial plane for the single BH) is assumed to be aligned with that of the circumbinary disk. The magnetic field is defined as anchored in the disk; hence, its associated magnetic dipole is aligned with the orbital and spin angular momentum.

As we are primarily interested in the dynamics close to the merger, we adopt initial data such that it takes place after about one orbit. These data describe quasiequilibrium, equal-mass, nonspinning black holes constructed by the publicly available LORENE code [22]. The black holes have masses given by $M_s = M/2$, and are initially separated by $\approx 6M$, lying beyond the approximate innermost stable circular orbit (ISCO) [23]. The initial magnetic field is poloidal and constructed from the electromagnetic potential produced by a circular loop, whose radius is assumed to be larger than the domain of interest [24]. We assume the disk lies at $\simeq 10^3 M$ and so $B^i \simeq B_o \hat{z}$. The

electric field is initially zero throughout and the magnetic field strength adopted is $B_o = 10^4 (M/10^8 M_\odot)$ G, which is within values inferred in relevant astrophysical systems (see, e.g., [25]).

We adopt a cubical domain given by $[-125M, 125M]^3$ and employ an AMR configuration with 7 levels of refinement that adjust themselves dynamically to ensure that the solution's error is below a predetermined threshold using a shadow hierarchy. Residuals of the various constraints and convergence of the physical fields with resolution are checked as tests of the code.

Results.—For concreteness we present the results of a single black hole with spin parameter $a = 0.7/M_s$. We adopt this value, which is slightly larger than the final spin expected for a merged black hole [26] for comparison purposes. The evolution shows an initial transient, where the EM fields adapt to the geometry of the black hole spacetime, giving rise to an electric field and a deformation of the magnetic field (see also [27,28]). After $t \simeq 40$–$60M$ the solution is clearly seen to evolve towards a quasistationary state determined by Wald's solution [29] for a Kerr black hole immersed in a uniform magnetic field which is aligned with its spin. Figure 1 presents the electric field obtained at $t = 200M$ in the plane $y = 0$. For comparison purposes, the corresponding field from Wald's exact solution is shown for $x > 0$. The apparent agreement along with a careful examination of the asymptotic solution indicates that, for a black hole immersed within an almost uniform magnetic field aligned with its spin, the final state is Wald's solution [27].

Next, we consider a binary black hole system at a quasicircular stage representing a late inspiral. In the present work, we adopt initially nonspinning equal-mass black holes to explore the dynamics of the system in a simple configuration. The initial electromagnetic field is defined in exactly the same manner as in the single black hole case. The evolution of this system, however, is significantly different as the orbiting black holes stir the fields
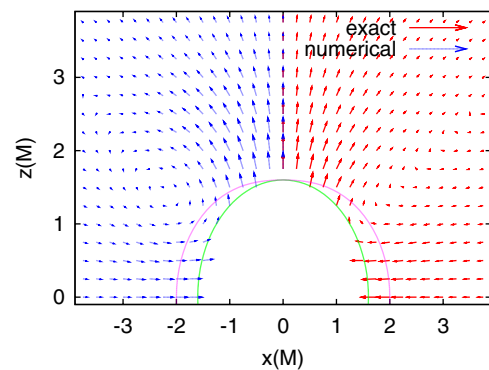

FIG. 1 (color online). The electric field for $y = 0$, $z \geq 0$ at $t = 200M$ for a single black hole, together with the apparent horizon (lower curve) and the ergosphere (upper curve). The region $x < 0$ displays the numerical solution, while Wald's exact solution is $x > 0$.
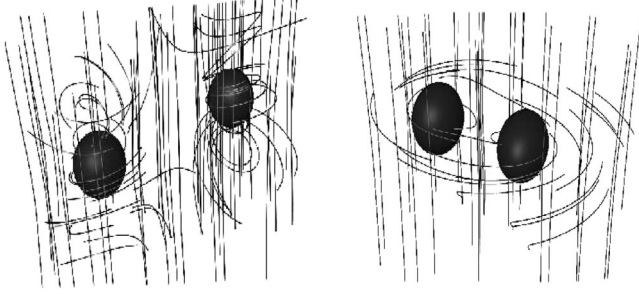
FIG. 2. Magnetic and electric field lines at $t \simeq -40M$, $-20M$ in 3D (the merger happens at $t = 0$). The electric field lines are twisted around the black hole, while the magnetic lines are mostly aligned with the z axis.

during the inspiral. Examples of the field configurations during the evolution are provided in Fig. 2.

To analyze the influence of the binary's dynamics on the electromagnetic field we monitor two particular quantities. One is the electromagnetic energy density $E^2 + B^2$, while the other is the radial component of the Poynting vector, S^r (radial from the origin). The former is employed to get a sense of the energy variation in the EM field, while the latter is used to examine the induced multipolar structure and for comparisons to the gravitational wave signal computed from the Newman-Penrose scalar, Ψ_4. (We additionally compute the analogous EM Newman-Penrose radiative quantity Φ_2 and confirm that the same features are present in it as in the Poynting vector.) Note that since the magnetic field is anchored in the disk, the magnetic field does not decay with the distance from the binary, and this obscures the standard interpretations drawn from the Poynting field. Nevertheless, the field does serve to elucidate the mode structure induced by the dynamics.

An examination of these quantities reveals several distinct features during the evolution. After an initial transient signal, and well before the merger takes place, the electromagnetic fields display a pattern consistent with those produced by electric dipoles, pointing along the orbital plane in the direction orthogonal to their velocity, orbiting about each other. This can be understood from the "membrane paradigm" point of view [30], in which the stretched horizon is endowed with a surface density of electrical charge and a surface resistivity. The quasicircular trajectories of the black holes cause a charge separation in the direction perpendicular to both the velocity and magnetic field, as in the Hall effect. In particular, the evolution induces a toroidal electric field (E_ϕ) with strength given by $B_z v_{\text{orbital}} c^{-1}$. These fields would seed a Blandford-Znajek type mechanism and generate energy when interacting with a surrounding medium. Additionally, the electric and magnetic fields oscillate with a frequency equal to the dominant frequency of the gravitational radiation. Since the Poynting flux is determined by the square of the electromagnetic fields, its oscillation pattern has a frequency that is twice that of the dominant gravitational

wave signal, and can be described in terms of $l = 0$, $m = 0$ and $l = 2$, $m = 0$ modes. As the merger approaches, an $l = 2$, $m = \pm2$ mode is induced and the peak of EM radiated energy lags behind the gravitational one by $t \simeq 2M$ [$1 \times 10^{-5}(M/M_\odot)$ s] with the same frequency (see Fig. 3). This lag time is likely related to the transition time from the binary black hole system to a single black hole, measured as the "time of flight" from the ISCO to the light ring. Indeed estimates of the ISCO and the light ring (lr) for $a = 0.67/M$ reveals $\Delta = r_{\text{ISCO}} - r_{\text{lr}} \simeq 1.5M$. Additionally, an enhancement of the electromagnetic field energy is clearly visible in the binary case, which displays a $\simeq 30\%$–40% increase with respect to the single case, as illustrated in Fig. 4. (We conjecture that in the presence of gas and black hole spins, this number could significantly increase.) At late times, the system asymptotes to the same solution observed for the single black hole.

Final comments.—We have analyzed the behavior of electromagnetic fields influenced by the dynamics of a binary black hole system. Our study illustrates several interesting aspects of such systems that emit not only gravitational waves, but can also radiate electromagnetically when interacting with a plasma.

The EM fields have a clearly discernible pattern tied to the dynamics, making them additional tracers of the spacetime, as these features would imprint particular characteristics in processes producing observable EM signals. In particular, in the premerger stages, the black hole dynamics induce electromagnetic (EM) energy flux oscillations with a period half that of the dominant gravitational wave (GW) signal produced by the system, i.e., a fourth of the orbital period, and a gradual enhancement of the energy in the electromagnetic field. During the merger, additional structure is impressed on the field, yielding a distinct pattern that lags behind the gravitational wave output by a time consistent with the characteristic time from the ISCO to the light ring of the merged black hole [31].
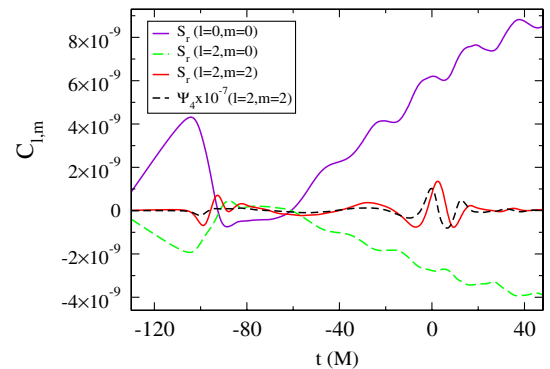

FIG. 3 (color online). The radial component of the Poynting vector for the binary black hole case. The structure reveals it is dominated by (spherical harmonic) EM$c_{0,0}$ and EM$c_{2,0}$ modes in the orbiting stage though close to merger a EM$c_{2,2}$ is induced which lags behind the corresponding gravitational wave (spin-2 spherical harmonic) GW$c_{2,2}$. The transient behavior before $t \simeq -100$ is spurious and due to the initial data employed.
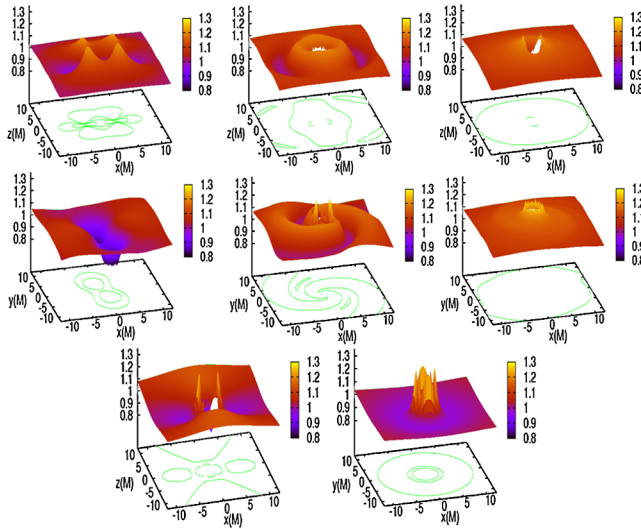
FIG. 4 (color online). Normalized electromagnetic energy density (with respect to its value at the initial time in the absence of black holes). The first and second row correspond to $y = 0$ and $z = 0$, respectively, at times $t \simeq -70$, 5, and $30M$. The last row corresponds to the single black hole case at $t = 150M$ for the sake of comparison. Normalized energy contour plots are shown with lines from 1.2 to 0.8 at intervals of 0.1. Around the merger epoch, the energy computed for the binary case is $\simeq 30\%$–40% larger than in the single case.

The distinct variability of the electromagnetic field as it is dragged by the black holes suggests tantalizing prospects to detect premerger electromagnetic signals from systems detectable in the gravitational wave band. At a more speculative level, these combined signals could be exploited to study alternative theories where photons and gravitons might propagate at different speeds (for a recent discussion of some possibilities, see [32,33]). A complete description of the problem requires the incorporation of gas and radiation effects. However, the main qualitative features—driven by the orbiting behavior of the black holes, whose inertia is many orders of magnitude above all else—would intuitively remain unaltered. The same reasoning also indicates the qualitative features described above will be present in non-equal-mass binaries. However, the presence of spin could introduce further features, as energy could be extracted from the individual black holes prior to merger. Ongoing [34] and related work will help to test these conjectures and shed further light on the problem.

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