Mergers of Magnetized Neutron Stars with Spinning Black Holes: Disruption, Accretion, and Fallback

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We investigate the merger of a neutron star in orbit about a spinning black hole in full general relativity with a mass ratio of 5:1, allowing the star to have an initial magnetization of 10^{12} G. We present the resulting gravitational waveform and analyze the fallback accretion as the star is disrupted. We see no significant dynamical effects in the simulations or changes in the gravitational waveform resulting from the initial magnetization. We find that only a negligible amount of matter becomes unbound; 99% of the neutron star material has a fallback time of 10 seconds or shorter to reach the region of the central engine and that 99.99% of the star will interact with the central disk and black hole within 3 hours.

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Introduction.—The spectacular energetics associated with short gamma ray bursts (SGRBs) are difficult to explain, requiring complex models synthesizing a variety of different components (see, e.g., [1–3]). Key among these is the inclusion of extreme gravity responsible for accelerating plasma to high Lorentz factors. Consensus is building for a scenario in which the gravitational field results from the merger of two highly compact objects: either a black hole and a neutron star (BH-NS) or a binary neutron star system (NS-NS). These systems radiate strongly in electromagnetic and gravitational wave bands making them ideal candidates for combined observations (e.g., [4]). The validation of such models requires a careful comparison of both electromagnetic and gravitational wave signatures with theoretical predictions.

Such predictions require sophisticated simulations incorporating the necessary physics ingredients. At the minimum they require solving the full, nonlinear field equations of general relativity along with hydrodynamics for a relativistic fluid. For the particular case of BH-NS, numerical models have recently begun achieving interesting success, and, despite the complexity of the parameter space involved, a common picture is emerging towards connecting the system with SGRBs. For instance, recent results indicate that the disk resulting from the merger of a nonspinning black hole with a neutron star (approximated by a Γ-law ideal fluid) is far less massive than what leading SGRB models require [5–7]. On the other hand, if the black hole is (sufficiently highly) spinning, the resulting disk is significantly more massive and falls within values consistent with the leading SGRB models resulting from BH-NS merger (e.g., [8–10]. Complementary efforts to understand possible electromagnetic counterparts are actively being investigated (e.g., [11–13]).

Beyond the importance for their connection to SGRBs, BH-NSs are also one of the most likely sources of detectable gravitational waves with earth-based gravitational wave detectors. Similar to binary black hole coalescence, BH-NS mergers (with a black hole mass above $\simeq 10 - 20 M_\odot$) are bright gravitational wave sources, expected to demonstrate remarkable sensitivity to the details of the neutron star due to tidal effects within the most sensitive frequency window of these detectors (e.g., [9,14,15]).

These systems are complex with a diverse phenomenology. Indeed, the equation of state of the fluid, the spin of the black hole, a nonvanishing magnetic field, and neutrino cooling all can influence the dynamics of the system. Different studies have been presented to explore the phenomenology related to the first two points above. In the current work we further explore these options and examine the behavior and possible impact of the star's magnetic field throughout the merger with a BH, employing our General Relativistic-MagnetoHyDrodynamics code. This allows us to study the system with effects that dominate the dynamics (general relativity and hydrodynamics) together with magnetic effects which may play a role through the merger and early postmerger. We explore the dynamics of material disrupted from the star. We estimate typical fallback times, and consider whether the observed dynamics is consistent with processes suggested as drivers of sustained emissions from SGRBs (e.g., [13,16–18]).

We model the neutron star material using relativistic ideal MHD, coupled to Einstein equations to represent the strong gravitational effects during the merger. Our numerical techniques have been thoroughly described and tested previously [19–22].

Setup.—We consider a binary system composed of a black hole (with $a/M = 0.5$) and a possibly magnetized neutron star (adopting $\Gamma = 2$). We begin with a quasicircular initial configuration constructed with LORENE [23]. We adopt a realistic mass ratio [24] $q \equiv M_{\rm NS}/M_{\rm BH} = 1/5$, and, for the magnetized cases, we add an initial, poloidal magnetic field to the neutron star by assuming a purely azimuthal vector potential of the form $A_\varphi = \varpi^2 \max(P - P_{\rm vac}, 0)$, [25] with ϖ the cylindrical radius and pressure $P_{\rm vac}/c^2 \simeq 10^4$ g/cm^3. This yields a field confined to the stellar interior with maximum magnitude of 10^{12} G. The BH has spin 0.5 and mass $M_{\rm BH} = 7.0 M_\odot$. The neutron star baryon (gravitational) mass is $1.473 M_\odot$ ($1.334 M_\odot$). The total mass of the system (black hole mass plus neutron star gravitational mass) is therefore $M_T \equiv M_{\rm BH} + M_{\rm NS} = 8.33 M_\odot$ and compactness (M/R) is 0.1; therefore, the initial BH and NS are of comparable physical extent.

The initial data are evolved in a cubical computational domain defined by $x^i \in [-443{\rm km}, 443{\rm km}]$, and we employ adaptive mesh refinement which tracks the two compact objects. However, once the star disrupts, the fluid is no longer localized which constrains the coarsest grid spacing. We adopt a coarse grid with spacing of $\Delta = 2.952$ km which covers the entire computational domain. Higher resolution is achieved by adopting 3 further levels of refinement for which the finest spacing has $\Delta = 0.738$ km (convergence comparisons were made with respect to runs with just 1 and 2 levels of refinement).

Results.—We focus primarily on the case in which the BH has spin aligned with the orbital angular momentum. We note that the main features discussed next are essentially the same for both magnetized and unmagnetized cases except at low density values; thus, unless noted the results discussed above stand for both cases.

For our spinning black hole configuration, *estimates* of the locations of the innermost stable circular orbit (ISCO) [15,26] and the mass-shedding limit [27] indicate that both are at comparable distances from the BH ($\simeq (3.36, 2.86) M_T$ respectively). Thus, the NS is expected to disrupt about the same time that it crosses the ISCO. Were the BH not spinning, the merger proceeds quickly with little mass remaining in any accretion disk.

As shown in Fig. 1, the neutron star orbits the BH for about two orbits and tidal disruption begins at time $t \simeq 9$ milliseconds. We extract the resulting gravitational wave signal by computing the Newman-Penrose Weyl scalar ψ_4 at different coordinate radii on our grid and then decomposing onto an appropriate spin-weight -2 basis. The dominant mode of this signal is illustrated in Fig. 2 (left). Until about $\simeq$12 ms when the star approaches the ISCO, one sees a signal generally characteristic of the quadrupole radiation of two orbiting masses. However, the star then crosses the ISCO and soon after begins to shed. This leads to a rapid decrease in the gravitational wave output [5,8,28]. Notice that the familiar ring-down pattern observed in binary black hole mergers is essentially absent due to the continuous infall of material.

Figure 2 (right) displays the power spectrum of the gravitational wave strain. Also shown with vertical bars are estimates of two frequencies, $f_{\rm isco}$ and $f_{\rm qnm}$, which characterize the system. These are obtained via simple first-principles estimates based on orbital frequencies corresponding to ISCO and "light-ring" locations or by examining the obtained solution. As discussed in [15,26] a simple estimate can be obtained by an "angular momentum balance" argument at the ISCO for the two-body problem, ignoring radiative and disruption effects. This estimate provides a value for the final BH spin of $\simeq$0.7 which gives $f_{\rm isco} \simeq 1100$ Hz. An accurate number, on the other hand, can be obtained by a direct inspection of the horizon geometry at $t = 27.3$ ms which indicates a ratio of polar to equatorial circumference of the BH of 0.931. This ratio corresponds to a BH with spin $a/M = 0.56$ which would instead indicate $f_{\rm isco} \simeq 880$ Hz. We thus expect a qualitative (smooth) change in the wave strain in this range of frequencies as the system transitions from an orbiting pair to an accreting BH, and indeed our spectrum shows such a change as the overall slopes before and after these frequencies are markedly different ($\approx -1/6$ vs ≈ -3.5). (Notice however early oscillations are evident due to both eccentricity from the initial configuration and neutron star oscillations.) Similarly, the estimates of $f_{\rm qnm}$—for the dominant quasinormal frequency—for a BH with spin $a/M = (0.56, 0.7)$ are $\simeq (1900, 2100)$ Hz.

Additionally, as the system is asymmetric, there is a net flux of momentum carried out by the gravitational waves, which results in the final hole acquiring a recoil velocity. A 2PN estimate of the kick [29] to 900 Hz gives $\simeq$2 km/s which is expected as this value does not take into account the merger stage. The value computed from the extracted waveform is $\simeq 40$ km/s which is below $\simeq$150 km/s that would be estimated for a binary black hole system with otherwise equal physical parameters [30]. That the BH-NS recoil value obtained is lower than

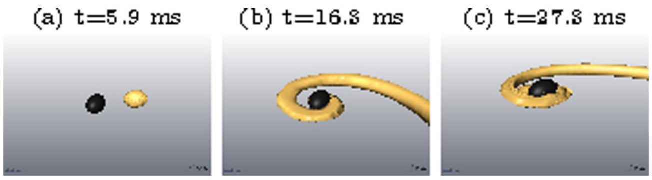


FIG. 1 (color online). An isosurface of density (6.18×10^{10} g/cm^3) and the apparent horizon (black spheroid) at various times for the magnetized evolution.

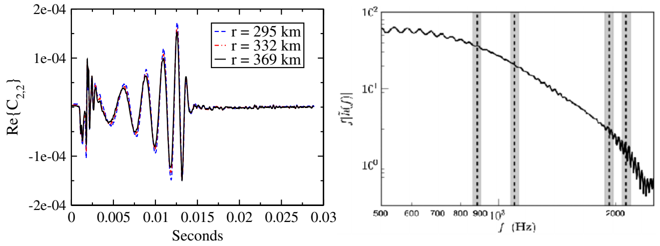


FIG. 2 (color online). (left) The $l = 2$, $m = 2$ mode of $r\Psi_4$ for mergers examined here (removing the initial artificial stage related to the initial data). Both the magnetic and nonmagnetic waveforms are the same; extraction performed at coordinate distances 295 km, 332 km, and 369 km and adjusted for travel time. (right) Power spectrum of the wave-strain $f|h|$ in which in grey bands denote frequencies associated with the ISCO and quasinormal ringing corresponding to a black hole with mass $M_T = 8.33M_\odot$ and spin of $a/M_T = (0.56, 0.7)$.

the analogous BH-BH system is expected as the former radiates less energy and momentum than the latter.

A significant amount of the NS matter is accreted through the merger, and the spin of the BH increases. As mentioned, the horizon geometry indicates a BH with spin $a/M_T = 0.56$. This value is consistent with the analogous case for a binary BH merger for which a simple model predicts a final BH spin of $a = 0.7M$ [26]. That the value here is smaller is expected because the angular momentum of the fluid outside the BH is not captured.

As a result of the merger, for the spinning cases a significant amount of matter ($0.17M_\odot$) at about $t \simeq 20$ ms is observed, regardless of the magnetization considered. Of this, we can estimate that a disk is formed with a mass equal to about 1% of the initial stellar mass (based on the integrated fluid mass on the finest resolution mesh about the black hole). However, we note that significantly more mass than this, about $0.07M_\odot$, remains outside the black hole as shown for the magnetized case in Fig. 3 for late times (times $t \simeq 30$ ms). The vast majority of this material has remained gravitationally bound to the black hole forming a reservoir that will eventually return to interact with the central engine (see also [10]).

It is useful to examine more closely the disk structure, temperature and velocity profile. We find that the structure consists of a hot and vertically thick region where material in the spiral arm has shocked due to intersection of stream lines while much of the tidal debris remains thin and cold prior to shocking. The temperature, estimated from the ratio of pressure to density, varies between 10^{10}–10^{12} K while the tidal tail of material thrown off is substantially cooler, around $\sim 10^8$ K. The velocity profile of the disk and tidal tail in both magnetic and nonmagnetic cases is shown in Fig. 4. As the merger and subsequent disk formation proceeds the magnetic field is redistributed into a toroidal configuration and grows through magnetic winding. Figure 4(a) illustrates the magnetic field structure at $t = 22.2$ ms. Furthermore, as a result of the disruption and merger process, a significant amount of matter is thrown out of the region close to the BH but most all of it (greater than 99%) remains bound as its speed is below the escape speed of the BH. This bound material will eventually interact with the central engine again. We calculate a fallback time for individual fluid elements based on the method detailed in [16]. Figure 5 shows distributions of the disrupted matter for a few times in the BH-NS merger (tidal disruption of the NS has begun by 8.9 ms while the spiral arm of tidal debris is well-formed at 16.3 ms). These distributions indicate that the accreted mass follows a power law in fallback time such that the accretion rate falls off with exponent about $-5/3$; we find a similar exponent in the case of a nonspinning black hole as well. This value equals that of Phinney [31] for accretion of material stripped from a main sequence star by a supermassive black hole This agreement is quite interesting due

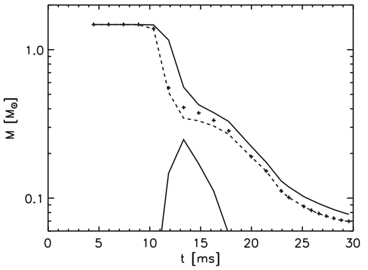
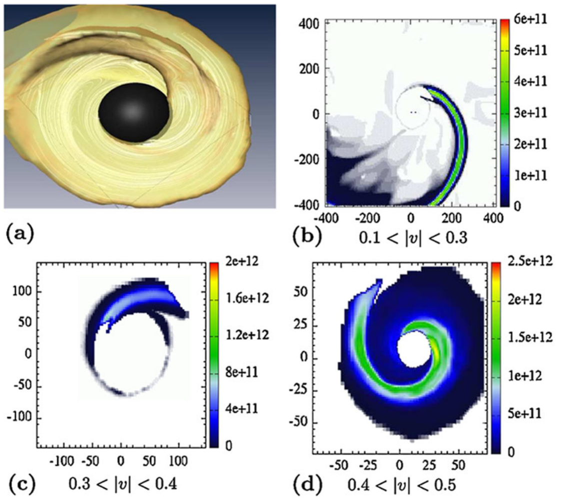


FIG. 3. The integrated mass (solid line) vs time for the magnetic case. The plus signs indicate the integral of material only outside the ISCO. The dashed curve shows the integral only over material moving slower than the escape speed for a 7 solar mass black hole. The dotted-dashed line (lowest curve) indicates unbound material (moving at or faster than the escape speed, regardless of direction) multiplied by a factor of 4 to put it on the same scale. The equivalent integrals for the unmagnetized simulation yield nearly identical values up to $t \simeq 20$ ms.



(a) (b) $0.1 < |v| < 0.3$

(c) $0.3 < |v| < 0.4$ (d) $0.4 < |v| < 0.5$

FIG. 4 (color online). Behavior at $t = 22.2$ ms (axis in kms and density color key in g/cm^3). (a) density isosurface and magnetic field lines with the black hole indicated by the central black spheroid. (b)–(d) fluid density grouped according to the speed of the fluid in the equatorial plane. There is no fluid with velocity more than 0.5.

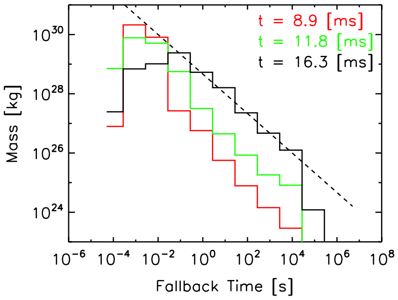


FIG. 5 (color online). Fallback accretion histogram. For all bound mass beyond 1.5 times the ISCO, a fallback time is estimated and the results are binned as shown. Distributions are computed for 3 times shown by the different colors that roughly correspond to the start of the tidal disruption event, the peak of gravitational radiation emitted from the system and the point where a disk encircles the central black hole. The dashed line indicates a power law with a slope of $-2/3$ for reference.

to a number of differences between the system studied in [31] and here: (i) our estimates derive from a relativistic evolution; (ii) our BH is spinning; (iii) our system is in a quasicircular orbit, not parabolic; (iv) our disrupted star is a NS, and (v) the mass ratio is far closer to unity such that the physical sizes of the BH and NS are comparable. This calculation suggests, in particular, that a significant amount of mass ($\approx 10^{-2} M_{\odot}$) will fall back between 1 s and about three hours.

Final comments.—Our results, together with other studies of BH-NS mergers [6,8,9], indicate that BH-NS systems with realistic mass ratios give rise to a sufficiently massive disk for connecting with SGRBs if the spin of the black hole is sufficiently high (otherwise the mass in the resulting disk decreases considerably). For these cases, gravitational waves from the system manifest subtle differences in the waveforms tied to the equation of state of the star as the mass-shedding radius is not far from the ISCO. Detecting such differences, however, requires delicate work on the data analysis front as the frequency window in which these differences arise is small. This issue is also encountered in binary neutron star systems [28]. Furthermore, the observation that the burst in gravitational waves might not be followed by quasinormal black hole ringing bears relevance to data analysis pipelines adopting different models to capture the burst behavior [32,33].

It is interesting to consider these results in the context of SGRBs. Our study indicates several interesting stages: (i) at early times in the merger ($\simeq 10^{-2}$–10^{-1} s), the BH hyperaccretes suggesting it might be a good candidate for creating a fireball through neutrino annihilation based on the mass accretion rate and remnant mass [34]; (ii) at later times ($\leq 10^{2}$ s), sufficient mass falls back which might support long sustained emissions via r processes, consistent with observed emissions in roughly 30% of SGRBs [18]; (iii) at even later times ($> 10^{2}$ s up to about 10^{3} s), there remains enough bound mass (roughly $10^{-2} M_{\odot}$) to be consistent with estimates of electromagnetic merger counterparts to gravitational waves [13].

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