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, 2]). 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. [1]). 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. A the minimum, they require solving the full, nonlinear field equations of general relativity along with relativistic hydrodynamics. 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 non-spinning BH with a NS (approximated by a Γ-law ideal fluid) is far less massive than what leading sGRB models require [3, 4]. On the other hand, if the BH 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. [5, 6]; see [7, 8] for recent reviews on the subject). Complementary efforts to understand possible observable electromagnetic counterparts are being investigated (e.g. [9, 10]).

Beyond the importance for their connection to sGRBs, BH-NSs are also one of the most likely sources of detectable gravitational waves with current and near-future earth-based gravitational wave detectors. Similar to binary black hole coalescence, BH-NS mergers (with a black hole mass above \( \approx 10 - 20M_{\odot} \)) are very bright gravitational wave sources, but they are also 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. [11, 12, 13, 14]).

These systems are complex with a diverse phenomenology. Indeed, the equation of state of the fluid, the spin of the BH, a nonvanishing magnetic field, and neutrino cooling all can have a profound influence on 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 study the possible impact of the star’s magnetic field throughout the merger with a BH, employing our General Relativistic-Magnetohydrodynamics code (GRMHD). This allow 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. In particular, we estimate typical fall back times, and consider whether the observed dynamics is consistent with processes suggested as drivers of sustained emissions after the main burst from sGRBs (e.g. [15, 16, 17]).

We model the neutron star material using relativistic ideal MHD, coupled to the full Einstein equations of general relativity to accurately represent the strong gravitational effects during the merger. Our numerical techniques for solving these coupled equations have been...
thoroughly described and tested previously [23, 27].

Set-up. We consider a BH-NS system where the neutron star is possibly magnetized and described by $\Gamma = 2$. We begin with quasi-circular initial data constructed with Lorene [28]. We adopt a realistic mass ratio $q \equiv M_{\text{NS}}/M_{\text{BH}} = 1/5$, and, for the magnetized cases, we add an initial, poloidal magnetic field to the neutron star by assuming a purely azimuthal vector potential as $A_\phi = \varpi^2 \max(P - P_{\text{vac}}, 0)$, [30] with $\varpi$ the cylindrical radius and pressure $P_{\text{vac}}/c^2 \approx 10^4$ 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 $M_{\text{BH}} = 7M_\odot$. The neutron star baryon (gravitational) mass is 1.473 \left(1.334\, M_\odot\right)$. The total mass of the system (BH mass plus NS gravitational mass) is $M_T \equiv M_{\text{BH}} + M_{\text{NS}} = 8.33M_\odot$ and compactness (M/R) is 0.1.

The initial data are evolved in a cubical computational domain defined by $x^i \in [-443\,\text{km}, 443\,\text{km}]$, and we employ adaptive mesh refinement which tracks the two compact objects. However, once the star disrupts, the fluid is no longer particularly localized which constrains the size of the grid spacing of the coarsest level. We adopt a coarse grid with spacing of $\Delta = 2$ centered at the horizon at $t=27.3\,\text{ms}$ which indicates a ratio of point to equatorial circumference of the BH of 0.931. This ratio corresponds to a BH with spin $a/M = 0.56$ which would indicate $f_{\text{isco}} \approx 880\text{Hz}$. We thus expect a qualitative (smooth) change in the waveform 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 $\approx -3.5$). (Notice however early oscillations are evident due to both eccentricity from the initial configuration and neutron star oscillations) Similarly, the estimates of $f_{\text{qnm}}$—for the dominant quasi-normal frequency—for a BH with spin $a/M = (0.56, 0.7)$ are $\approx (1900, 2100)\text{Hz}$. 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 [34] to 900Hz gives $\approx 2\text{km/s}$ which is expected as this value does not take into account the merger stage. The actual value computed from the extracted waveform is $\approx 40\text{ km/s}$ which is below $\approx 150\text{km/s}$ that would be estimated for a binary black hole system with otherwise equal physical parameters [35]. That the BH-NS recoil value obtained is lower than 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 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 $t \approx 9$ milliseconds. We extract the resulting gravitational wave signal by computing the Newman-Penrose Weyl scalar $\psi_4$ at different coordinate radii and then decomposing onto an appropriate spin-weight $-2$ basis. The dominant mode of this signal is illustrated in Fig. 2 (left). Until about $\approx 12$ 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, 10, 33]. Notice that the familiar ringdown pattern observed in binary black hole mergers is essentially absent due to the continuous in-fall of material.

Figure 2 (right) displays the power spectrum of the gravitational wave strain. Also shown with vertical bars are estimates of two frequencies, $f_{\text{isco}}$ and $f_{\text{qnm}}$ 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 [19, 31] 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 $\approx 0.7$ which gives $f_{\text{isco}} \approx 1100\text{Hz}$. An accurate number, on the other hand, can be obtained by a direct inspection of the horizon at $t=27.3\,\text{ms}$ which indicates a ratio of poloidal to equatorial circumference of the BH of 0.931. This ratio corresponds to a BH with spin $a/M = 0.56$ which would indicate $f_{\text{isco}} \approx 880\text{Hz}$. We thus expect a qualitative (smooth) change in the waveform 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 $\approx -3.5$). (Notice however early oscillations are evident due to both eccentricity from the initial configuration and neutron star oscillations) Similarly, the estimates of $f_{\text{qnm}}$—for the dominant quasi-normal frequency—for a BH with spin $a/M = (0.56, 0.7)$ are $\approx (1900, 2100)\text{Hz}$. 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 [34] to 900Hz gives $\approx 2\text{km/s}$ which is expected as this value does not take into account the merger stage. The actual value computed from the extracted waveform is $\approx 40\text{ km/s}$ which is below $\approx 150\text{km/s}$ that would be estimated for a binary black hole system with otherwise equal physical parameters [35]. That the BH-NS recoil value obtained is lower than the analogous BH-BH system is expected as the former radiates less energy and momentum than the latter.

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through the merger process, and the spin of the BH consequently 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 \(a = 0.7M_\odot\) [31]. That the value here is smaller is expected because the angular momentum of the fluid remaining outside the BH is not captured.

As a result of the merger, for the spinning cases a significant amount of matter (0.17\(M_\odot\)) at about \(t \approx 20\) 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 for both the magnetic and non-magnetic cases (based on the integrated fluid mass on the finest resolution mesh about the BH). However, we note that significantly more mass than this, about 0.07\(M_\odot\), remains outside the BH as shown for the magnetized case in Fig. 3 for late times (times \(t \approx 30\) ms). The vast majority of this material has remained gravitationally bound to the BH forming a reservoir that will eventually return to interact with the central engine (see also [32]).

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 non-magnetic 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 4a 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 [20]. Fig. 5 shows distributions of the disrupted matter for a few times during the evolution (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 non-spinning BH as well. This value equals that of Phinney [30] for accretion of material stripped from a main sequence star by a supermassive BH. This agreement is quite interesting due to a number of differences between the system studied in [30] and here: (i) our estimates derive from a relativistic evolution; (ii) our BH is spinning; (iii) our system is in a quasi-circular orbit, not parabolic; (iv) our disrupted star is a NS, not a main sequence star and (v) the mass-ratio is far closer to unity such that the physical sizes of the BH and NS are comparable.

**Final comments.** Our results, together with other studies of BH-NS mergers [8,10,11], 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 BH is sufficiently high (otherwise the mass in the resulting disk decreases considerably). For these cases, gravitational waves from the system will 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, will require delicate work on the data analysis front as the frequency window in which these differences will arise is quite small. This issue is also encountered in binary neutron star systems [33]. Furthermore, the observation that the burst in gravitational waves might not be followed by quasinormal black hole ringing bears relevance to burst searches in data analysis pipelines adopting different models to capture the burst behavior [37,38].

It is interesting to consider these results in the context of short GRBs. Our evolutions of BH-NS mergers indicate several interesting stages: (i) at early times in the merger (\(\sim 10^{-2} - 10^{-1}\) 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 [38]; (ii) at later times (\(\lesssim 10^2\) s), sufficient mass will be falling back which might support long sustained emissions via r-processes, consistent with observed emissions in roughly 30% of short GRBs [22]; (iii) at even later times (> 10^3 s up to about 10^4 s), there remains enough bound mass (roughly \(10^{-2} M_\odot\)) to be consistent with estimates of electromagnetic merger counterparts to gravitational waves [17].

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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 BH. The dot-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 $t \approx 20\text{ms}$.

FIG. 4: System behavior at $t=22.2\text{ ms}$ (axis in kms and density color key in units of $g/cm^3$). (a) density isosurface and magnetic field lines with the BH 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.

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[1] E. Berger, ArXiv e-prints (2010), 1005.1068.
[2] P. Mészáros, Reports on Progress in Physics 69, 2259 (2006).
[3] W. H. Lee and E. Ramirez-Ruiz, New Journal of Physics 9, 17 (2007).
[4] L. S. Collaboration et al. (Virgo), Astrophys. J. 715, 1438 (2010).
[5] M. Shitaba et al., Phys. Rev. D (2009).
[6] T. Yamamoto, M. Shibata, and K. Taniguchi, Phys. Rev. D78, 064054 (2008).
[7] M. Shibata and K. Uryu, Phys. Rev. D74, 121503 (2006).
[8] M. Shibata and K. Uryu, Class. Quant. Grav. 24, S125 (2007).
[9] F. Löffler, L. Rezzolla, and M. Ansorg, Phys. Rev. D74, 104018 (2006).
[10] Z. B. Etienne et al., Phys. Rev. D79, 044024 (2009).
[11] M. Duez et al., 2009, arXiv:0912.3528 [astro-ph].
[12] E. Rantsiou et al., Astrophys. J. 680, 1326 (2008).
[13] J. Faber, Class. Quant. Grav. 26, 114004 (2009).
[14] M. D. Duez, Class. Quant. Grav. 27, 114002 (2010).
[15] L. Li and B. Paczyński, Astrophys. J. 507, L59 (1998).
[16] E. Berger, Astrophys. J. 690, 231 (2009).
[17] B. D. Metzger et al., 2010, 1001.5029.
[18] M. Vallisneri, Phys. Rev. Lett. 84, 3519 (2000).
[19] C. Hanna, et al., Class. Quant. Grav. 26, 015009 (2009).
[20] S. Rosswog, Mon. Not. Roy. Astron. Soc. Lett. 376, L48 (2007).
[21] W. H. Lee and E. Ramirez-Ruiz, New J. Phys. 9, 17 (2007).
[22] B. D. Metzger et al., 2009, 0908.0530.
[23] M. Anderson, et al., Class. Quant. Grav. 23, 6503 (2006).
[24] C. Palenzuela, et al., Phys. Rev. D75, 064005 (2007).
[25] S. L. Liebling, Phys. Rev. D66, 041703 (2002).
[26] M. Anderson, et al., Phys. Rev. D77, 024006 (2008).
[27] M. Anderson et al., Phys. Rev. Lett. 100, 191101 (2008).
[28] http://www.lorene.obspm.fr.
[29] F. Ozel, et.al., [arXiv:1006.2834] [astro-ph.GA].
[30] M. Shibata, et.al., Phys. Rev. D74, 104026 (2006).
[31] A. Buonanno, L. E. Kidder, and L. Lehner, Phys. Rev. D77, 026004 (2008).
[32] K. Taniguchi, et.al., Phys. Rev. D77, 044003 (2008), 0710.5169.
[33] J. S. Read et al., Phys. Rev. D79, 124033 (2009).
[34] E. Racine, A. Buonanno, and L. E. Kidder, Phys. Rev. D80, 044010 (2009).
[35] C. O. Lousto, M. Campanelli, and Y. Zlochower, Class. Quant. Grav. 27, 114006 (2010).
[36] E. S. Phinney, in The Center of the Galaxy, edited by M. Morris (1989), vol. 136 of IAU Symposium, pp. 543–. Kluwer, Dordrecht, Netherlands
[37] F. Beauville et al. (LIGO-Virgo working group), Class. Quant. Grav. 25, 045002 (2008).
[38] E. Chassande-Mottin, et.al., (2010), 1005.2876.
[39] R. Popham, S. E. Woosley, and C. Fryer, Astrophys. J. 518, 356 (1999), arXiv:astro-ph/9807028.