ASTRONUM 2016 IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **837** (2017) 012010 doi:10.1088/1742-6596/837/1/012010

The status of general relativistic simulations of compact binary mergers as engines of short gamma-ray bursts

Vasileios Paschalidis*

Department of Physics, Princeton University, Princeton, NJ 08544, USA

E-mail: *vp16@princeton.edu

Abstract. Black hole - neutron star (BHNS) and neutron star - neutron star (NSNS) binaries are perhaps the most popular progenitors for short-hard gamma ray bursts. After about two decades of numerical relativity simulations of binary compact objects we are beginning to understand the necessary ingredients for jets to emerge from these systems following merger. We report on the latest development of this field summarizing the results from state-of-the-art numerical relativity (magnetohydrodynamic) simulations of compact binary mergers as progenitors of short-hard gamma-ray bursts.

1. Introduction

A few months ago, the LIGO and Virgo collaborations marked the beginning of the era of gravitational wave astronomy with the announcement of the detection of two signals that were consistent with the gravitational wave (GW) signal generated by the inspiral and merger of binary black hole systems [1, 2]. Over the next few years, GWs are expected to also be detected from neutron star–neutron star (NSNS) and black hole–neutron star (BHNS) binary mergers. The merger rates for these binaries are uncertain but upper limits have been estimated to 12,600 (3,600) $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for NSNS (BHNS) [3].

Inspiraling and merging NSNSs and BHNSs are sources not only of GWs, but also of electromagnetic (EM) signals that can be generated prior to [4, 5, 6, 7, 8, 9] and after [10, 11] merger. The detection of both GW and EM signals arising from the same source would provide a wealth of information about the source, test relativistic gravitation (see e.g. [12]), and constrain the nuclear equation of state (EOS) (see e.g. [13]) among other things.

Among the different EM signals NSNSs and BHNSs may have, a short gamma-ray burst (sGRB) is the one these systems are particularly famous for. It is widely accepted that NSNS and BHNS are the most likely progenitors of sGRBs [14, 15, 16, 17, 18, 19, 20]. A simultaneous detection of an sGRB with a GW consistent with the coalescence of a BHNS or NSNS system would solidify the BHNS and NSNS binaries as the progenitors of sGRBs. However, due to the merger rates of these objects such an association may require a lucky nearby event or third-generation GW observatories [19]. Until then, studying these binaries via simulations in full general relativity is the only reliable avenue for gaining a complete theoretical understanding of these systems as sGRB engines. However, this involves a large number of obstacles that have to be overcome. For example one needs to solve the Einstein equations for the spacetime metric [10 partial differential equations (PDEs)] coupled to the energy-momentum and neutrino transport equations (8 PDEs), coupled to Maxwell's equations for the electromagnetic field (8 PDEs), coupled to baryon number conservation (1 PDE) for a total of 27 coupled PDEs in 3+1 dimensions. In fact the neutrino transport equation is 6+1 dimensional problem because in addition to the 3 spatial and one temporal dimension it has two angular and one frequency (energy) dimension. Note that above we even excluded the lepton number conservation equations and that the entire system need to be supplemented with a hot nuclear equation of state, which complicate the problem even further. Modern codes that are able to solve all or a subset of the above equations adopt a finite volume approach (typically third-order accurate or higher) for the (magneto)hydrodynamics, and (fourth-order accurate or higher)finite difference or pseudo-spectral methods for the Einstein equations. Other unique challenges of modeling compact binaries in full general relativity involve the presence of physical singularities – infinities, when evolving BH spacetimes and the choice of appropriate coordinates. However, many of these problems are now under control due to the development of sophisticated theoretical and computational numerical relativity tools (see [21] for a textbook). As far as modeling these objects as sGRB engines is concerned, simulations indicate that general relativity, and magnetic fields are crucial for launching jets (see below). Recent simulations in [22] suggest that neutrinos are unable to power outflows following NSNS mergers, and inefficient at driving jets following BHNS mergers. However, neutrinos can launch winds that make the funnel area above the black hole less baryon loaded. As a result neutrinos may be important for the magnetic fields to be able to ultimately accelerate jets to the Lorentz factors of $O(100)$, which are necessary for explaining sGRB phenomenology.

In recent years a large number of NSNS and BHNS numerical relativity simulations have augmented our understanding of the processes involved in these mergers. Despite the challenge posed (see e.g. [23] for a detailed discussion) due to the very high-resolution requirements necessary to capture the relevant magnetic effects, the large range of length and time scales involved in the problem and because of a very challenging neutrino transport problem that has to be solved, with the current tools and available codes we have taken great strides toward understanding the necessary ingredients for jet launching following BHNS and NSNS mergers. Here, we will provide a status report of numerical relativity (magneto)hydrodynamic simulations of compact binary mergers as sGRB engines, and summarize what has been learned so far.

The article is structured as follows: In Sec. 2 we present results from recent simulations of binary BHNSs and in Sec. 3 results from recent simulations of binary NSNSs. We conclude in Sec. 4 with a brief summary and list of open questions. Unless otherwise specified, below we adopt geometrized units where $G = c = 1$.

2. BHNS mergers

For a review of simulations of BHNS binaries we refer the reader to [24]. Here we focus on simulations of these binaries as sGRB engines. The first numerical relativity simulations testing the viability of BHNSs as progenitors of sGRB engines, addressed the question of whether quasicircular, irrotational BHNSs (the NS is practically non-spinning, but the BH can be spinning) can form a sizable accretion disk outside the remnant BH. Having a disk outside the BH is necessary to form the BH-disk engine that is thought to power the sGRB. Even a small fraction of the accretion power can account for typical sGRB luminosities: $L_\gamma = \epsilon \dot{M} c^2 \sim 10^{51}\mathrm{erg/s}(\epsilon/0.01)(M_{\rm disk}/0.1M_\odot)(t_{\rm acc}/1\mathrm{s})^{-1}$, where ϵ is a conversion efficiency from accretion power to gamma-ray luminosity, $M_{\rm disk}$ the disk mass, and $t_{\rm acc}$ the accretion time scale. But, forming a disk outside the BH is not trivial, because this requires that the NS tidal disruption occur outside the innermost stable circular orbit (ISCO) of the remnant BH, and this is possible only for small BH to NS mass ratios, and for binaries either involving rapidly spinning BHs and/or NSs with small compaction [25, 26].

Multiple BHNS simulations have investigated the BHNS parameter space in which a relatively large amount matter can remain outside the BH following the NS tidal disruption. and the results were summarized in [27], who derived fitting formulae for predicting the disk mass onto the BH. The main finding can be summarized as follows: *at the most likely BH to NS mass ratio* ($7:1$) *the disk mass will be* $\sim 0.1M_\odot$ *only if the initial BH dimensionless spin is* $a = J_{\rm BH}/M_{\rm BH}^2 \gtrsim 0.8$, which can be a very tight constraint.

This result holds for quasicircular, irrotational BHNSs which probably dominate the rates of BHNS mergers in the Universe. However, recent work [28, 29, 30] argues that in galactic nuclei and globular clusters (GCs), compact binaries can merge with sizable eccentricities at rates which may be relevant for GW detection [31, 32]. It is also plausible that mergers in GCs could account for up to $\sim 30\%$ of the observed sGRBs [33] (see also [34, 35, 36]). Thus, the progenitors of a fraction sGRBs may be eccentric compact objects mergers occurring in GCs. An additional aspect of GC NSs is that $\gtrsim 80\%$ of pulsars in GCs in our Galaxy have millisecond spin periods, and hence compact binary mergers in GCs involving neutron stars are likely to occur with rapidly spinning neutron stars [37, 38, 39].

Using the above as motivation, numerical relativity hydrodynamic simulations of the final encounter of hydrodynamic eccentric BHNS mergers in full general relativity with $4:1$ mass ratio have been performed in [31, 32], and in [37] where the effects of the NS spin were considered for the first time. Depending on the value of the pericenter distance, the amount of disk mass found in these simulations ranges from $\sim 1\% - 20\%$ of the NS rest mass even for non-spinning BHs, and for stiffer equations of state it can be even 30%. We note that a $4:1$ mass ratio, quasi-circular BHNS merger with a non-spinning NS results in negligibly small accretion disk [27]. Thus, eccentric BHNS mergers as may occur in GCs can form BH-disk engines more easily than quasi-circular binaries.

However, showing that compact binary mergers involving NSs can form a BH-disk system is one requirement for demonstrating viability of BHNSs as progenitors of sGRBs. The second requirement is to demonstrate that jets can be launched by the resulting BH-disk systems – a necessary ingredient for many models of sGRBs [17]. Next we describe efforts to demonstrate jet launching via numerical relativity magnetohydrodynamic simulations of BHNS mergers.

The first MHD simulations of BHNSs in full general relativity were performed in [41], who did not report jet formation after simulating for ~ 30 ms. The first detailed, numerical relativity studies exploring the parameter space of magnetized BHNSs with MHD simulations in full general relativity were performed in [42, 43]. These studies endowed the initial neutron star with a dipole magnetic field restricted in the interior of the star. The results about jet emergence were negative, even when the maximum initial magnetic field pressure at the center was 5% of the gas pressure! The lack of jets was initially attributed to the resolution being too low to capture the magnetorotational instability (MRI) in the remnant disk. However, even when increasing the resolution to resolve the MRI wavelength by 10 grid points – which has been found empirically to suffice for capturing the basic effects of MRI – again no jet was found. More recent MHD simulations of BHNSs in full general relativity [44] that adopt even higher resolution, and resolve the fastest growing MRI mode, confirmed the results of [42, 43].

These results were very intriguing because for over 15 years, fixed-spacetime GRMHD accretion flows onto BHs showed that jets are a natural outcome [45]. So, what is the problem with accretion disks formed following BHNS mergers?

The answer to this question is simple: for a magnetized torus with magnetic fields initially restricted in its interior, a jet is launched only for special magnetic field geometries, and in particular, a magnetic field with a vertical component having consistent sign is necessary [46]. Thus, if one seeded toroidal magnetic fields in the torus no jets would be launched [46]. What happens in a BHNS merger is that during and following the NS disruption is that the bulk of the magnetic energy is swallowed by the BH during the main merger event, while the initially

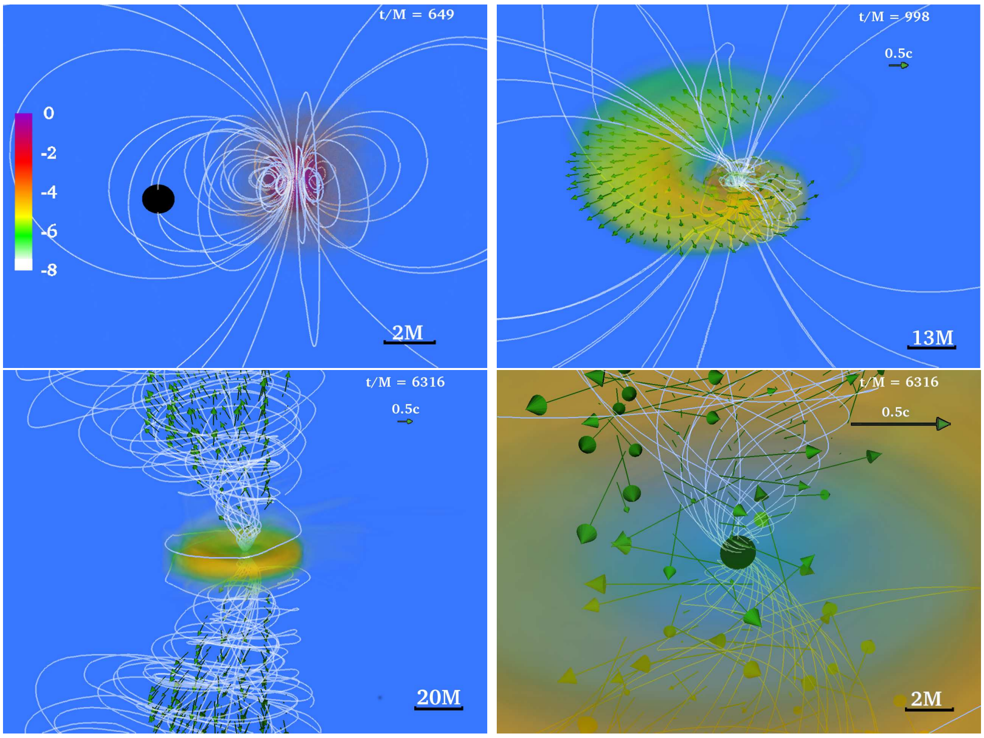

Figure 1. Snapshots of the ratio of the rest-mass density divided by its initial maximum value $\rho_{0,\rm max} = 8.92 \times 10^{14}(1.4M_\odot/M_{\rm NS})^2$g cm^{-3} (log scale). Arrows designate matter velocities and white curves the magnetic field lines. The bottom panels show the system after an incipient jet has been launched. Here, M $= 2.5 \times 10^{-2}(M_{\rm NS}/1.4M_\odot)ms= 7.58(M_{\rm NS}/1.4M_\odot)$km. Figure from [40].

poloidal magnetic field in the remaining matter is stretched and wound into an almost purely toroidal geometry. Therefore, per the results of [46] no jets can be launched.

The missing link was finally found in [40], who made the realization that these early BHNS simulations adopted magnetic fields restricted in the NS interior. However, pulsars suggest that a more realistic magnetic field geometry is a dipole extending from the NS interior well into its exterior [40]. While this sounds like it would be a straightforward change, it is not trivial for ideal MHD codes to evolve magnetic-field dominated regions as would be required in a magnetosphere. For this reason, the authors in [40] designed new types of initial conditions, which satisfy one aspect of magnetic-field dominance, namely the magnetic field dominates the pressure in the exterior atmosphere, but not the energy density. These atmospheric initial conditions allow the evolution of exterior magnetic fields with an ideal GRMHD code, and via a sequence of simulations varying the degree of magnetic-pressure dominance one can test the validity of the results as the force-free regime is approached [40]. This is the procedure developed and followed by [40], who performed MHD simulations of BHNS mergers in full GR and demonstrated that an incipient jet launched about ~ 100 ms following the BHNS merger (see Fig. 1). Interestingly, the disk lifetime was found to be $\sim$0.5 s, and the jet EM luminosity 10^{51} erg/s, i.e., consistent with characteristic sGRB values. The flow was only mildly relativistic $\Gamma_L \sim 1.3$, hence the term "incipient". However, the magnetization in the incipient jet outflow was $B^2/8\pi\rho c^2 \sim 100$, and $B^2/8\pi\rho c^2$ is a crucial ratio because it approximately equals the terminal Lorentz factor of a magnetically powered jet [47]. Thus, the jets found in [40], in principle can be accelerated to the Lorentz factors required to explain sGRB phenomenology. Therefore, BHNSs can indeed be

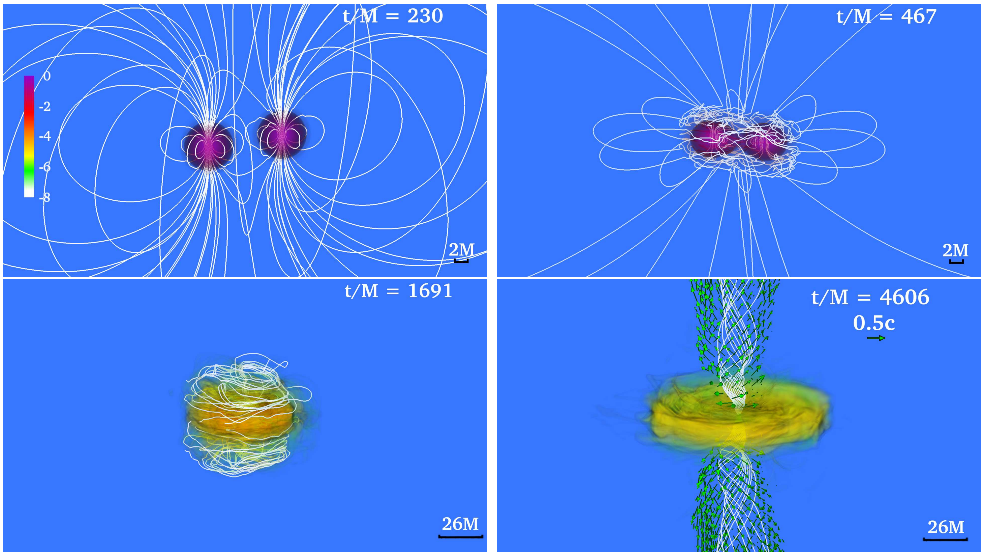

Figure 2. Same as in Fig. 1, but here $\rho_{0,\rm max} = 5.9 \times 10^{14}(1.625\,M_\odot/M_{\rm NS})^2$ g cm^{-3} and $M = 1.47 \times 10^{-2}(M_{\rm NS}/1.625M_\odot)$ ms $= 4.43(M_{\rm NS}/1.625M_\odot)$ km. The appearance of an organized, large scale magnetic field inside the incipient jet is clear in the bottom right panel. Figure from [50].

the progenitors of sGRBs!

3. Simulations of NSNS mergers

For a comprehensive review of simulations of NSNS binaries we refer the reader to [48], as well as [49] for a more recent review. Here we focus on work related to NSNS mergers as sGRB engines and in particular on the latest MHD simulations in full GR.

Only few numerical relativity MHD simulations of NSNSs have been performed. Early MHD calculations of NSNS mergers in full general relativity reported the emergence of "jet-like structures" [51]. This means the formation of a structure resembling a funnel, but no jet outflow was reported. A recent high-resolution MHD study of NSNS mergers in full GR [52] reports that even when the MRI is captured the fallback material has so strong a ram pressure that not only a jet cannot be launched, but also a wind cannot be launched (unlike in BHNSs where winds are possible). More recent MHD simulations of NSNSs in full GR [53, 54], also do not find jets, however the initial magnetic fields were too weak to resolve MRI.

Motivated by the jet emergence in the BHNS calculations of [40], [50] adopted similar methods for the magnetic field initial data and evolution as in [40], but this time in a NSNS setting adopting the same matter and spacetime initial data as those in [51]. The authors report that MRI operates and that about 60 ms after merger, an incipient jet emerges even in this NSNS scenario (see Fig. 2). The accretion timescale in this simulation was found to be ~ 0.2 s, and the jet EM luminosity 10^{51} erg/s – again consistent with characteristic values from sGRBs. The magnetization in the collimated outflow was $B^2/8\pi\rho c^2 \sim 100$, implying that terminal Lorentz factors of $\Gamma_L \sim 100$ could potentially be achieved. Also, consistent with the findings of [52] the authors found that the jet emerged shortly after the ambient density of the fallback matter decreased to levels satisfying $B^2/(8\pi\rho c^2) \gg 1$.

We note here, that unlike the other numerical relativity MHD studies of NSNSs that do not report jet launching, the authors of [50] endowed the neutron stars with magnetar-strength magnetic fields. While such fields are high by pulsar standards, they are still dynamically unimportant initially, thus offering a natural means to equipartition-level magnetic fields in the post-merger hypermassive neutron star. These high magnetic fields in the hypermassive neutron star are expected to naturally arise because of the Kelvin-Helmholtz instability (KHI) and the MRI operating during and after merger, respectively [55, 56]. Thus, [50] argued that if the KHI and MRI have sufficient time to operate and amplify the post-merger magnetic field to equipartition levels, then a jet is possible following BH formation.

4. Conclusions and future challenges

Numerical relativity simulations of NSNSs and BHNSs over the last 15 years have improved our understanding of how these binaries may form the BH-disk engines that can power jets and explain sGRBs. The works of [40, 50] have provided the first "existence proofs" that BHNSs and NSNSs can form jet engines and hence are viable progenitors of sGRBs. However, these works endowed the initial neutron stars with magnetic fields that are larger by a couple of orders of magnitude than typical inferred pulsar magnetic fields. Even though such strong magnetic fields are dynamically unimportant and hence one would expect the results to scale to weaker field strengths, these calculations should be performed with weaker magnetic fields to corroborate the results. But, this would then require much better grid resolutions (almost 10 times better) to be able to resolve all the MHD processes. Using such high resolution would make these simulations at best impractical. However, as more accurate numerical methods are adopted and the scaling is improved, and as the computers become faster such simulations should be possible within the next decade. Furthermore, it is very difficult to accurately evolve magnetically dominated areas with ideal MHD codes. Thus, simulations including magnetic fields extending from the NS interior out to its exterior should also be revisited with more sophisticated methods (perhaps with resistive MHD codes [57, 58]).

Despite the great progress, open questions always remain and here is an incomplete list: Do the incipient jets persist for an accretion timescale? How can incipient jets reach $\Gamma_L \gtrsim 100$? What mechanisms give rise to the prompt gamma ray emission? Do neutrinos play any role? These and many other questions pose the challenge for future simulations modeling compact binaries as sGRB engines.

Acknowledgments

This work was supported by NSF grant PHY-1607449, the Simons Foundation, and NASA grant NNX16AR67G (Fermi).

References

[1] Abbott B P *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) 2016 *Phys. Rev. Lett.* **116**(6) 061102 URL `http://link.aps.org/doi/10.1103/PhysRevLett.116.061102`
[2] Abbott B P *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) 2016 *Phys. Rev. Lett.* **116**(24) 241103 URL `http://link.aps.org/doi/10.1103/PhysRevLett.116.241103`
[3] Abbott B P *et al.* (Virgo, LIGO Scientific) 2016 *Astrophys. J.* **832** L21 (*Preprint* `1607.07456`)
[4] Hansen B M and Lyutikov M 2001 *Mon.Not.Roy.Astron.Soc.* **322** 695 (*Preprint* `astro-ph/0003218`)
[5] McWilliams S T and Levin J 2011 *Astrophys. J.* **742** 90 (*Preprint* `1101.1969`)
[6] Paschalidis V, Etienne Z B and Shapiro S L 2013 *Phys. Rev. D* **88** 021504 (*Preprint* `1304.1805`)
[7] Palenzuela C, Lehner L, Ponce M, Liebling S L, Anderson M, Neilsen D and Motl P 2013 *Physical Review Letters* **111** 061105 (*Preprint* `1301.7074`)
[8] Ponce M, Palenzuela C, Lehner L and Liebling S L 2014 *Phys. Rev. D* **90** 044007 (*Preprint* `1404.0692`)
[9] Metzger B D and Zivancev C 2016 *Mon. Not. R. Astron. Soc.* **461** 4435–4440 (*Preprint* `1605.01060`)
[10] Metzger B D and Berger E 2012 *Astrophys. J.* **746** 48 (*Preprint* `1108.6056`)
[11] Metzger B D, Bauswein A, Goriely S and Kasen D 2015 *Mon. Not. R. Astron. Soc.* **446** 1115–1120 (*Preprint* `1409.0544`)
[12] Yunes N, Yagi K and Pretorius F 2016 *ArXiv e-prints* (*Preprint* `1603.08955`)
[13] Lackey B D and Wade L 2015 *Phys. Rev. D* **91** 043002 (*Preprint* `1410.8866`)

[14] Eichler D, Livio M, Piran T and Schramm D N 1989 *Nature* **340** 126–128
[15] Narayan R, Paczynski B and Piran T 1992 *Astrophys. J. Lett.* **395** L83–L86 (*Preprint* astro-ph/9204001)
[16] Mochkovitch R, Hernanz M, Isern J and Martin X 1993 *Nature* **361** 236–238
[17] Meszaros P 2006 *Rept.Prog.Phys.* **69** 2259–2322
[18] Lee W H and Ramirez-Ruiz E 2007 *New Journal of Physics* **9** 17 (*Preprint* astro-ph/0701874)
[19] Berger E 2014 *Ann. Rev. Astron. Astroph.* **52** 43–105
[20] Paschalidis V, Ruiz M and Shapiro S L 2015 *Astrophys. J. Lett.* **806** L14 (*Preprint* 1410.7392)
[21] Baumgarte T W and Shapiro S L 2010 *Numerical Relativity: Solving Einstein's Equations on the Computer* (Cambridge University Press)
[22] Just O, Obergaulinger M, Janka H T, Bauswein A and Schwarz N 2015 *ArXiv e-prints* (*Preprint* 1510.04288)
[23] Paschalidis V 2016 (*Preprint* 1611.01519)
[24] Shibata M and Taniguchi K 2011 *Living Reviews in Relativity* **14** 6–+
[25] Etienne Z B, Faber J A, Liu Y T, Shapiro S L, Taniguchi K *et al.* 2008 *Phys.Rev.* **D77** 084002
[26] Etienne Z B, Liu Y T, Shapiro S L and Baumgarte T W 2009 *Phys. Rev. D* **79** 044024 (*Preprint* 0812.2245)
[27] Foucart F 2012 *Phys. Rev. D* **86** 124007 (*Preprint* 1207.6304)
[28] Lee W H, Ramirez-Ruiz E and van de Ven G 2010 *Astrophys. J.* **720** 953–975 (*Preprint* 0909.2884)
[29] Kocsis B and Levin J 2012 *Phys. Rev. D* **85** 123005 (*Preprint* 1109.4170)
[30] Samsing J, MacLeod M and Ramirez-Ruiz E 2014 *Astrophys.J.* **784** 71 (*Preprint* 1308.2964)
[31] Stephens B C, East W E and Pretorius F 2011 *Astrophys. J. Lett.* **737** L5 (*Preprint* 1105.3175)
[32] East W E, Pretorius F and Stephens B C 2012 *Phys. Rev. D* **85**(12) 124009 URL http://link.aps.org/doi/10.1103/PhysRevD.85.124009
[33] Grindlay J, Portegies Zwart S and McMillan S 2006 *Nature Physics* **2** 116–119 (*Preprint* astro-ph/0512654)
[34] Narayan R, Paczynski B and Piran T 1992 *Astrophys. J.* **395** L83 astro-ph/9204001 (*Preprint* astro-ph/9204001)
[35] Gehrels N *et al.* 2005 *Nature* **437** 851–854 (*Preprint* arXiv:astro-ph/0505630)
[36] Lee W H, Ramirez-Ruiz E and Granot J 2005 *Astrophys. J. Lett.* **630** L165–L168 (*Preprint* arXiv:astro-ph/0506104)
[37] East W E, Paschalidis V and Pretorius F 2015 *Astrophys. J. Lett.* **807** L3 (*Preprint* 1503.07171)
[38] Paschalidis V, East W E, Pretorius F and Shapiro S L 2015 *Phys. Rev. D* **92** 121502 (*Preprint* 1510.03432)
[39] East W E, Paschalidis V, Pretorius F and Shapiro S L 2016 *Phys. Rev. D* **93** 024011 (*Preprint* 1511.01093)
[40] Paschalidis V, Ruiz M and Shapiro S L 2015 *Astrophys. J. Lett.* **806** L14 (*Preprint* 1410.7392)
[41] Chawla S, Anderson M, Besselman M, Lehner L, Liebling S L, Motl P M and Neilsen D 2010 *Physical Review Letters* **105** 111101–+
[42] Etienne Z B, Liu Y T, Paschalidis V and Shapiro S L 2012 *Phys.Rev.* **D85** 064029
[43] Etienne Z B, Paschalidis V and Shapiro S L 2012 *Phys.Rev.* **D86** 084026
[44] Kiuchi K, Sekiguchi Y, Kyutoku K, Shibata M, Taniguchi K and Wada T 2015 *Phys. Rev. D* **92** 064034 (*Preprint* 1506.06811)
[45] Abramowicz M A and Fragile P C 2013 *Living Reviews in Relativity* **16** URL http://www.livingreviews.org/lrr-2013-1
[46] Beckwith K, Hawley J F and Krolik J H 2008 *Astrophys. J.* **678** 1180–1199
[47] Vlahakis N and Königl A 2003 *Astrophys. J.* **596** 1080–1103
[48] Faber J A and Rasio F A 2012 *ArXiv e-prints* (*Preprint* 1204.3858)
[49] Baiotti L and Rezzolla L 2016 *ArXiv e-prints* (*Preprint* 1607.03540)
[50] Ruiz M, Lang R N, Paschalidis V and Shapiro S L 2016 *Astrophys. J. Lett.* **824** L6 (*Preprint* 1604.02455)
[51] Rezzolla L, Giacomazzo B, Baiotti L, Granot J, Kouveliotou C and Aloy M A 2011 *Astrophys. J. Lett.* **732** L6
[52] Kiuchi K, Kyutoku K, Sekiguchi Y, Shibata M and Wada T 2014 *Phys.Rev.* **D90** 041502 (*Preprint* 1407.2660)
[53] Endrizzi A, Ciolfi R, Giacomazzo B, Kastaun W and Kawamura T 2016 *ArXiv e-prints:1604.03445* (*Preprint* 1604.03445)
[54] Kawamura T, Giacomazzo B, Kastaun W, Ciolfi R, Endrizzi A, Baiotti L and Perna R 2016 *Phys. Rev. D* **94** 064012 (*Preprint* 1607.01791)
[55] Zrake J and MacFadyen A I 2013 *Astrophys. J. Lett.* **769** L29 (*Preprint* 1303.1450)
[56] Kiuchi K, Cerd-Durn P, Kyutoku K, Sekiguchi Y and Shibata M 2015 *Phys. Rev.* **D92** 124034 (*Preprint* 1509.09205)
[57] Palenzuela C 2013 *Mon. Not. R. Astron. Soc.* **431** 1853–1865 (*Preprint* 1212.0130)
[58] Dionysopoulou K, Alic D, Palenzuela C, Rezzolla L and Giacomazzo B 2013 *Phys. Rev. D* **88** 044020