

# SHORT GAMMA-RAY BURSTS FROM THE MERGER OF TWO BLACK HOLES

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## ABSTRACT

Short Gamma-Ray Bursts (GRBs) are explosions of cosmic origins believed to be associated with the merger of two compact objects, either two neutron stars, or a neutron star and a black hole. The presence of at least one neutron star has long been thought to be an essential element of the model: its tidal disruption provides the needed baryonic material whose rapid accretion onto the post-merger black hole powers the burst. The recent tentative detection by the *Fermi* satellite of a short GRB in association with the gravitational wave signal GW150914 produced by the merger of two black holes has shaken this standard paradigm. Here we show that the evolution of two high-mass, low-metallicity stars with main sequence rotational speeds a few tens of percent of the critical speed eventually undergoing a weak supernova explosion *can* produce a short gamma-ray burst. The outer layers of the envelope of the last exploding star remain bound and circularize at large radii. With time, the disk cools and becomes neutral, suppressing the magneto-rotational instability, and hence the viscosity. The disk remains 'long-lived dead' until tidal torques and shocks during the pre-merger phase heat it up and re-ignite accretion, rapidly consuming the disk and powering the short gamma-ray burst.

*Subject headings:* gamma rays: bursts — accretion, accretion disks — gravitational waves — stars: black holes

## 1. INTRODUCTION

The recent detection of gravitational waves (GW) from the merger of a massive stellar binary black hole system (BH, Abbott et al. 2016) has opened a new window for the observation of the universe. The gravitational wave signal was determined to be produced by the final inspiral and ringdown of a binary system of two BHs of masses 36 and 29  $M_{\odot}$ , at a distance of 0.4 Gpc from Earth. The Gamma-Ray Burst monitor (GBM) on-board *Fermi* was serendipitously pointing, at that time, to a region of the sky that intersected with more than 70% of the error region from which the GW signal was detected. Analysis of the data revealed the presence of a mildly significant source of hard X-rays/soft gamma-rays 0.4 seconds after the GW event, lasting approximately 1 second (Connaughton et al. 2016). The chance significance of the transient is 0.002, or approximately 3 Gaussian standard deviations.

If true, the new source would have properties resembling a weak short-duration Gamma-Ray Burst (GRB). Its isotropically equivalent energy in the GBM band would amount to  $L_{\text{iso}} \simeq 2 \times 10^{49} \text{ erg s}^{-1}$ , about a factor 10 weaker than a typical short GRB, but not unprecedented (e.g., GRB080925A, D'Avanzo et al. 2014). While the intrinsic weakness of the burst energetics could suggest that the short GRB was seen off-axis and its true energy is much larger, the hardness of the spectrum requires instead that the burst is seen on-axis and the measured energy corresponds to the true energy budget of the event. If not due to a random fluctuation, the *Fermi* observation points therefore to the association of weak, mildly (if at all) collimated short GRBs with the merging of BH-BH binary systems.

Such association is somewhat surprising since general consensus requires the presence of at least one neutron star (NS) in the merging compact binary system that generates a gamma-ray bursts (Berger 2014). This requirement is motivated by the need of creating a post-merger BH-accretion disk system. In a NS-NS or NS-BH merger scenario, the

NS(s) would be tidally stripped of  $\sim 0.1 M_{\odot}$  of matter during the merger and provide the material for an accreting circum-BH torus (Rezzolla et al. 2010; Giacomazzo et al. 2013). In a clean, double BH merger case, the source of the accreting material was expected to be absent. Whether the association between GW150914 and the *Fermi* GBM candidate is real or not, it has however raised the possibility that BH-BH mergers may also produce SGRBs, unlike commonly thought. In this letter we show that such a scenario is possible within the standard theory of high mass evolution and accretion disks.

## 2. FORMATION OF A BINARY BH-BH WITH A FALLBACK DISK

In the following, we consider a typical evolutionary scenario that may lead to electromagnetic radiation in conjunction with a BH-BH merger. As a specific example, we adopt parameter values that would lead to a type of event such as GW150904, but clearly our considerations can be generalized to other initial conditions, and hence the specific model discussed here should simply be considered as a representative case of the new idea that we are proposing.

The starting point for this representative case is a high-mass binary system with stars of masses in the 30 to 40  $M_{\odot}$  range and metallicity  $Z \lesssim 0.1 Z_{\odot}$ . If the two stars were to evolve without interaction, such as in a detached binary, then, for this range of initial masses, a BH is generally expected to be formed either through a partial or a full fallback of the envelope (e.g. Fryer & Kalogera 2001; Heger et al. 2003). However, there are several other key properties of the stars beyond their initial masses, as well as elements of stellar evolution, which greatly influence this simple picture. In particular, metallicity plays a fundamental role in mass loss, since a higher metallicity results in stronger radiation-driven winds (e.g. Maeder 1992; Heger et al 2003), and at high metallicities NSs become an increasingly more common remnant. Additionally, the initial rotational velocity of the star also affects evolution, since it influences elemental mixing within the envelope, as well as angular momentum transport (e.g. De Mink

et al. 2009). The latter, as discussed more in the following, is also highly dependent on the uncertain role played by magnetic torques during the evolution of the star.

When stars evolve in a binary system, in addition to the elements discussed above, also binary interactions play an important role, and many studies have been devoted to model these interactions with various degrees of sophistication (for a review of the channels forming a double BH system, see e.g. Kalogera et al. 2007). If the stars are rapidly rotating and remain chemically homogeneous and compact throughout their lifetime without becoming giants, then they may evolve as in isolation (e.g. de Mink et al. 2009). However, in close binary systems in which stars evolve to the giant phase, the exchange between the two stars can be dramatic, including non-conservative mass transfer (e.g. Dominik et al. 2012).

However, despite these interactions, the evolution of the mass gainer star after the accretion episode is found to be almost identical to that of a star evolving in isolation with the same mass (Cantiello et al. 2007). In particular, these authors find that the angular momentum is very similar in the isolated and in the binary evolution cases. These similarities arise because, while the post-accretion, rejuvenated star is a bit more evolved than the isolated one, however this difference is small compared to the longer secular evolution, and it mainly results in a slightly reduced loss of spin down due to mass loss during core hydrogen burning.

Given the above, and lacking simulations of the pre-supernova (SN) interior structure of rotating stars in interacting binaries, here we consider some examples of the pre-SN structure of rotating, isolated stars. We emphasize that these models should be simply considered as illustrative of the conditions required in the interior of the star prior to its collapse for our scenario to work.

We have calculated the pre-SN star models using the evolutionary code MESA inclusive of rotation (Paxton et al. 2013). An important point to note is that these simulations include angular momentum transport via magnetic torques (Spruit 2002). However, the importance of these torques is still a subject of debate, and it may vary very well considerably from star to star. If magnetic torques are negligible during the evolution, then the specific angular momentum of the pre-SN star is considerably higher for the same initial conditions (see e.g. fig.4 of Perna et al. 2014), and therefore the requirement of low metallicity in our models would become less stringent.

Fig. 1 shows the distribution of the specific angular momentum in the interior of the star just prior to its explosion, for a main sequence star of mass  $M = 40 M_{\odot}$ , metallicity  $Z = 0.01 Z_{\odot}$ , and three values of the initial equatorial rotational speed. Also indicated is the specific angular momentum of a particle in a corotating orbit at radius  $R$  around a BH of spin parameter  $a = 0$  (dotted line) and  $a = 1$  (dashed line), where

$$j(R) = \frac{\sqrt{GMR} \left[ R^2 - 2(a/c) \sqrt{GMR/c^2} + (a/c)^2 \right]}{R \left[ R^2 - 3GMR/c^2 + 2(a/c) \sqrt{GMR/c^2} \right]^{1/2}}. \quad (1)$$

Here  $M$  is the mass of the BH and  $J = aM$  its angular momentum.

The pre-SN models of Fig. 1 are characterized by the fact that the outer envelope layers are endowed with a specific angular momentum  $j_m > j(R_{\text{iso}})$ , where  $R_{\text{iso}}$  is the radius at the last stable orbit. This is a structure that we envisage in at least one of the two stars, preferably the second one to go off as SN,

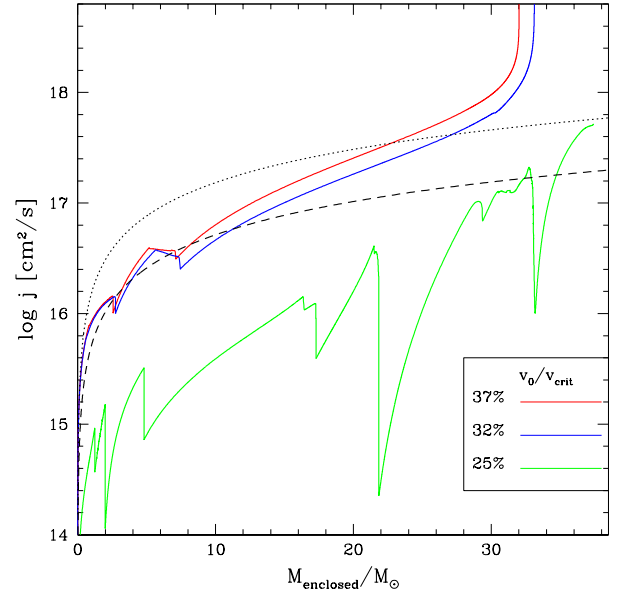


FIG. 1.— The distribution of specific angular momentum in a pre-SN star of mass  $M = 40 M_{\odot}$  and metallicity  $Z = 0.01 Z_{\odot}$ , for three initial values of the surface equatorial velocity of the main sequence star, expressed in units of the critical surface equatorial velocity (see Perna et al. 2014 for details). Also plotted is the specific angular momentum of a particle at the last stable orbit around a Schwarzschild (dotted line) and a Kerr (dashed line) black hole of mass  $M = M_{\text{enclosed}}$ .

since any fallback material left over from the first SN may be blown away when the second star explodes.

Before continuing, we should note that the idea that SN explosions may leave behind long-lived disks has a long history in the literature, dating as far back as Colgate (1971) and Chevalier (1989). However, the focus has always been on fallback disks around NSs rather than BHs, since the former display a wide range of observable phenomena which can be accounted for with such disks, from enhanced emission in the Anomalous X-ray Pulsars (Chatterjee et al. 2000; Alpar 2001), to anomalous braking indices in pulsars (Menou et al. 2001), to jets in pulsars (Blackman & Perna 2002), to transient pulsars (Cordes & Shannon 2008), to the making of planets (Lin et al. 1991). These long-lived fallback have been shown to be observable up to ages  $\sim 10^4 - 10^5$  years at long wavelengths, especially the infrared (Perna et al. 2000), and a detection of a fallback disk has indeed been made (Wang et al. 2006). In the context of BHs, the focus has traditionally been on the rapidly accreting, short-lived disks that power the long GRBs, since these are connected to a well established observational phenomenology. However, the possibility of long-lived disks also around BHs has been introduced by Perna et al. (2014). While the motivation there was to explore the possibility of planet formation around BHs, those calculations provide the context for forming a short GRB during a BH-BH merger, as it will be argued in the following.

In order to leave behind a BH of mass  $\sim 30 M_{\odot}$ , stars such as the ones considered in Fig.1 need to undergo a relatively weak explosion. For example, a star with  $M = 40 M_{\odot}$ ,  $Z = 0.01 Z_{\odot}$  and  $v = 37\%$  of the critical speed, would experience  $M_{\text{fb}} \gtrsim 30 M_{\odot}$  of mass in fallback for explosion energies  $E \leq 10^{51}$  erg (see fig.6 in Perna et al 2014). The outer layers of the envelope of these stars, endowed with angular momentum  $j_m > j(R_{\text{los}})$ , will fall back on a dynamical timescale and

eventually circularize at the radius  $R_{\text{circ}}$  where  $j_m = j(R_{\text{circ}})$ . The following evolution of the ring is mediated by viscosity, with a typical timescale

$$t_0(R_{\text{circ}}) = \frac{R_{\text{circ}}^2}{H^2 \alpha \Omega_K} \sim 160 \alpha_{-1}^{-1} m_{30}^{-1/2} R_{10}^{3/2} \left(\frac{R}{H}\right)^2 \text{ s}, \quad (2)$$

where  $R_{10} = R/(10^{10} \text{ cm})$ ,  $m_{30} = M/(30 M_\odot)$ ,  $H$  is the disk scale-height,  $\Omega_K$  is the Keplerian velocity of the gas in the disk, and  $\alpha$  the viscosity parameter in units of  $\alpha_{-1} \equiv \alpha/0.1$  (Shakura & Sunyaev 1973). The disk height is  $H \sim R$  during the early, hot super-Eddington slim disk phase, whereas it is  $H \sim 0.1 R$  once the disk, cooled by photons, becomes optically thick, geometrically thin. After a time  $t \sim t_0$ , the evolution of the disk accretion rate and outer radius can be well approximated with a power law (e.g. Cannizzo et al 1990),

$$\dot{M}_d(t) = \dot{M}_d(t_0) \left(\frac{t}{t_0}\right)^{-\beta} \quad (3)$$

$$R_d(t) = R_d(t_0) \left(\frac{t}{t_0}\right)^{\gamma}, \quad (4)$$

where  $\beta = 4/3$  and  $\gamma = 2/3$  apply during the early slim disk phase, and  $\beta = 19/16$  and  $\gamma = 3/8$  during the later geometrically thin regime.

As a specific, quantitative example, let us now consider the evolution of one of the pre-SN models shown in Fig.1, and in particular, the case with main sequence rotational speed equal to 37% of the critical speed. Assuming a weak explosion so that all the material falls back, we find that the outermost  $\sim 0.5 M_\odot$  of envelope circularizes at radii between  $\sim 10^9 - 5 \times 10^{10} \text{ cm}$ . The initial accretion rate is  $\dot{M}(t_0) \sim \dot{M}_d/t_0 \sim 6 \times 10^{-6} M_\odot \text{ s}^{-1}$ . The disk remains super-Eddington for about 90 years, and continues to cool with the accretion rate dropping and the mass gradually depleting.

Accretion can proceed as long as the temperature in the disk remains high enough to maintain the gas at least partially ionized. However, as the temperature drops and the magnetic diffusivity decreases, accretion becomes choked. Numerical simulations of the magneto-rotational instability (MRI, Balbus & Hawley 1991) have shown that, at low magnetic Reynolds numbers ( $\sim$  a few  $\times 10^3$ ) MHD turbulence and its associated angular momentum transport are significantly reduced (Hawley et al. 1996; Fleming, et al 2000). The power law evolution of the SN fallback disk gets interrupted, and the disk becomes 'dead'<sup>1</sup> (e.g. Menou et al. 2001). The precise value of the accretion rate at which this happens depends on the specifics of the opacity, and hence the composition of the pre-SN star. For a disk of solar composition, the local stability criterion is (Hameury et al. 1998)

$$\dot{M}_d(R) > \dot{M}_{\text{crit}}(R) \simeq 9.5 \times 10^{15} m_{10}^{-0.9} R_{10}^{2.68} \text{ g s}^{-1} \quad (5)$$

and slight variations are expected in the case of helium-rich and metal-rich disks (Menou et al. 2001). For the representative model discussed here, when the disk becomes 'dead' it still retains  $\sim 5.5 \times 10^{-4} M_\odot$  of its mass. Note that this is sufficient to power a GRB with observed luminosity  $L_{\text{iso}} \sim 2 \times 10^{49} \text{ erg s}^{-1}$  such as the one measured for the possible counterpart of GW150914.

From this point on, if the binary is not perturbed by external elements, it will live a long time as a system of two BHs with one surrounded by an inactive disk, until the final plunge rekindles the disk, as discussed in the following.

<sup>1</sup> Note that such a type of disk was detected around an isolated NS, with an estimated age  $\gtrsim 10^6$  years (Wang et al. 2006).

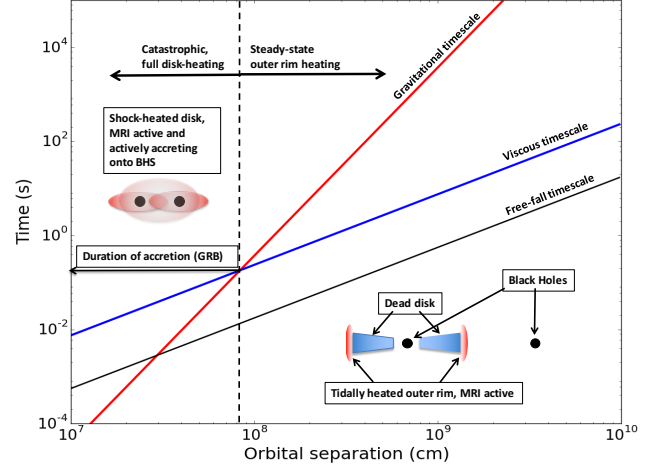


FIG. 2.— Comparison of the free-free, viscous, and gravitational inspiral timescales as a function of the orbital separation for a system of two  $M = 30 M_\odot$  black holes. One of the two BHs is assumed to be surrounded by a 'dead' fallback disk. The disk is reactivated once the gravitational timescale becomes smaller than the viscous one. From that point on the two BHs merge on the very short timescale  $t_{\text{GW}}$ , followed by an electromagnetic emission on the timescale  $t_{\text{visc}}$ .

### 3. THE FINAL SECONDS: MAKING A SGRB

Let us now consider the evolution of a binary black hole system with a 'dead' accretion disk surrounding one of the two black holes (analogous considerations hold for the case in which both BHs have accretion disks). If the outer radius of the accretion disk is smaller than the tidal truncation radius, the disk and the companion BH do not interact significantly (Paczynski 1977; Papaloizou & Pringle 1977; Ichikawa & Osaki 1994). We focus here on a binary black hole system with two identical black holes and with orbital separation  $r$ . We also assume that the disk and the binary orbits are in the same plane, even though a different geometry should not affect the conclusions of this argument. The tidal truncation radius in this case is  $r_{\text{TT}} \sim 0.3r$  (Paczynski 1977). For any reasonable parameter set, the viscous timescale at the outer rim of the disk (Eq. 2) is much shorter than the gravitational waves inspiral timescale  $t_{\text{GW}}$  (Hughes 2009; see Figure 2):

$$t_{\text{GW}} = \frac{5}{256} \frac{c^5}{G^3} \frac{r^4}{2m^3} = 0.37 \frac{r_8^4}{m_{30}^3} \text{ s}. \quad (6)$$

In this regime, the bare black hole excites tidal dissipation, concentrated in the outer rim of the accretion disk (Papaloizou & Pringle 1977; Ichikawa & Osaki 1994). The associated heating ionizes the outer rim of the disk turning on the MRI. Because the inner part of the disk is still neutral, the material in the outer rim cannot accrete, and hence piles up at the outer edge of the dead zone.

As long as  $t_{\text{GW}} > t_0$ , the system evolves in a quasi steady-state fashion, since the disk has time to adjust to the new BH-BH configuration, maintaining an MRI active outer rim pushing against an inactive and non-accreting inner disk. As the binary shrinks, it reaches a point at which  $t_{\text{GW}} \simeq t_0$ . From that moment on, the disk does not have time to adjust to the inspiral of the binary system and the tidal heating reaches the inner part of the disk, likely becoming an impulsive, shock-driven event rather than a quasi-stationary process, analogously to what seen in numerical simulations of extended disks surrounding a central binary BH (Farris et al. 2015).

The critical radius  $r_{\text{crit}}$  at which the two time-scales are

equal is readily derived from Eqs. 2 and 6:

$$r_{\text{crit}} = 3.45 \times 10^7 \left( \frac{R}{H} \right)^{4/5} \frac{m_{30}}{\alpha_{-1}^{2/5}} \text{ cm.} \quad (7)$$

The accretion phase is very rapid, since the disk is very compact due to the accumulation of material at the outer rim that took place during the inspiral. If accretion produces the launching of a relativistic jet – as seen in SGRBs (Berger 2014) and in tidal disruption events (Burrows et al. 2011) – and the relativistic jet radiates in gamma-rays, we can derive the burst duration from the viscous timescale at the critical radius, obtaining:

$$t_{\text{GRB}} = 0.005 \left( \frac{R}{H} \right)^{16/5} \frac{m_{30}}{\alpha_{-1}^{8/5}} \text{ s.} \quad (8)$$

For a relatively thin disk with, e.g.  $(R/H) \sim 3$  at the tidal truncation radius, Eq. 8 yields  $t_{\text{GRB}} = 0.2$  s, in good agreement with the Fermi transient associated to GW150914. The burst luminosity depends on the mass accretion rate, which in turns depends on the mass of the disk. A disk with a modest mass of  $\sim 10^{-4} - 10^{-3} M_{\odot}$ , such as the one discussed in Sect. 2, would be consistent with the observed luminosity for standard  $\sim 10\%$  efficiency values for the conversion of accretion power to relativistic outflow and of the outflow power into radiation.

#### 4. SUMMARY

The discovery of gravitational waves (Abbott et al. 2016) has opened a new window on the Universe, and the combined detection of GWs and EM radiation would enormously increase their diagnostic power. The possible detection by *Fermi* of a short GRB-like counterpart to GW150914 has been puzzling in light of the fact that no EM emission was expected from a double BH merger.

Here we have presented a new idea for a scenario which, starting from a binary system of two massive, low-metallicity stars, leads to two massive BHs, (at least) one of which is surrounded by a fallback disk at large radii. As the disk cools it eventually becomes neutral, the MRI is suppressed and the disk can then survive for a very long time as a ‘dead’ disk. Eventually, when the two BHs start their final dance towards the inexorable merger, tidal torques and shocks heat up the gas as the naked BH spirals inward plowing its way within the disk. Accretion resumes from the outer regions towards the inner ones, and the mass pile up propagates inwards as the inner parts of the disk get gradually revived. Immediately following the merger the disk is fully revived, and the mass piled up hence accretes very rapidly giving rise to a short Gamma-Ray Burst.

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#### REFERENCES

- Abbott, P. B. et al. 2016, PRL, 116, 061102  
 Alpar, M. A. 2001, ApJL, 557, L61  
 Balbus, S. A., Hawley, J. F. 1991, ApJ, 376, 214  
 Berger, E. 2014, ARA&A, 52, 43  
 Blackman, E. G., & Perna, R. 2004, ApJL, 601, L71  
 Burrows, D. N., Kennea, J. A., Ghisellini, G., et al. 2011, Nature, 476, 421  
 Cannizzo, J. K., Lee, H. M. & Goodman, J. 1990, ApJ, 351, 38  
 Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 543, 368  
 Chevalier, R. A. 1989, ApJ, 346, 847  
 Colgate, S. A. 1971, ApJ, 163, 221  
 Connaughton, V. et al. 2016, submitted  
 Cordes, J. M., & Shannon, R. M. 2008, ApJ, 682, 1152  
 D’Avanzo, P., Salvaterra, R., Bernardini, M. G., et al. 2014, MNRAS, 442, 2342  
 de Mink, S. E., Cantiello, M., Langer, N., et al. 2009, A&A, 497, 243  
 Dominik, M., Belczynski, K., Fryer, C., et al. 2012, ApJ, 759, 52  
 Farris, B. D., Duffell, P., MacFadyen, A. I., & Haiman, Z. 2015, MNRAS, 447, L80  
 Fleming, T. P., Stone, J. M., Hawley, J. F. 2000, ApJ, 530, 464  
 Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548  
 Giacomazzo, B., Perna, R., Rezzolla, L., Troja, E., & Lazzati, D. 2013, ApJ, 762, L18  
 Hameury, J.-M., Menou, K., Dubus, G., Lasota, J.-P. & Hureo, J.-M. 1998, MNRAS, 298, 1048  
 Hawley, J. F., Gammie, C. F., Balbus, S. A. 1996, ApJ, 464, 690  
 Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288  
 Hughes, S. A. 2009, ARA&A, 47, 107  
 Ichikawa, S., & Osaki, Y. 1994, PASJ, 46, 621  
 Kalogera, V., Belczynski, K., Kim, C., O’Shaughnessy, R., & Willems, B. 2007, PhR, 442, 75  
 Lin, D. N. C., Woosley, S. E., & Bodenheimer, P. H. 1991, Natur, 353, 827  
 Maeder, A. 1992, A&A, 264, 105  
 Menou, K., Perna, R., & Hernquist, L. 2001a, ApJL, 554, L63  
 Menou, K., Perna, R., & Hernquist, L. 2001b, ApJ, 559, 1032  
 Paczynski, B. 1977, ApJ, 216, 822  
 Papaloizou, J., & Pringle, J. E. 1977, MNRAS, 181, 441  
 Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4  
 Perna, R., Hernquist, L., & Narayan, R. 2000, ApJ, 541, 344  
 Perna, R., Duffell, P., Cantiello, M., MacFadyen, A. I., 2014, ApJ, 781, 119  
 Rezzolla, L., Baiotti, L., Giacomazzo, B., Link, D., & Font, J. A. 2010, Class. Quantum Grav., 27, 114105  
 Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337  
 Spruit, H. C. 2002, A&A, 381, 923  
 Wang, Z., Chakraborty, D., & Kaplan, D. 2006, Natur, 440, 772