Long Gamma Ray Bursts from binary black holes

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ABSTRACT

Aims. We consider a scenario for the longest duration gamma ray bursts, resulting from the collapse of a massive rotating star in a close binary system with a companion black hole.

Methods. The primary black hole born during the core collapse is first being spun up and increases its mass during the fallback of the stellar envelope just after its birth. As the companion black hole enters the outer envelope, it provides an additional angular momentum to the gas. After the infall and spiral-in towards the primary, the two black holes merge inside the circumbinary disk.

Results. The second episode of mass accretion and high final spin of the post-merger black hole prolongs the gamma ray burst central engine activity. The observed events should have two distinct peaks in the electromagnetic signal, separated by the gravitational wave emission. The gravitational recoil of the burst engine is also possible.

Key words. black hole physics; accretion; gamma ray bursts

1. Introduction

Gamma ray bursts are transient sources of extreme brightness observed on the sky with isotropic distribution. Their prompt phase lasts between a fraction of a second and few hundreds of seconds, and the long duration events are believed to originate from collapsing massive stars. In the collapsar model, a newly born black hole (BH) surrounded by a transient disk ac-

ematics by Zhang & Fryer (2001); Barkov & Komissarov (2010), in which three phases can be distinguished: the spiral-in of the BH inside the envelope, possibly with a spherical accretion of some surrounding gas and transfer of orbital angular momentum into the envelope; increase of the accretion rate through the high-angular momentum shells of matter onto the BH residing already, or newly born, in the center (see Chevalier 2012 for a description of a collapse event triggered by the inspiral of the compact object to the central core of the companion star); and final accretion of the remaining gas during the ultimate GRB explosion accompanied by the jet ejection. In addition to the electromagnetic signal, such a process will also be followed by a characteristic gravitational-wave signal due to the collapse of the core into the BH, but mostly because of the binary BH inspiral and merger.

This article is composed as follows: Sect. 2 describes the models used to estimate the basic parameters of the process. Sect. 2.2 describes a model of the BH surrounded by a torus, Sect. 2.3 considers the case of strong winds during the accretion of the in-falling shells. Sect. 2.4 gathers the pre-merger scenarios. The model of the binary BH merger is described in Sect. 3. Sect. 4 contains discussion and conclusions.

Through the text, the subscript 1 denotes the primary BH, a result of the collapse of the primary component in the binary sys-
tem. Subscript 2 denotes the companion BH, whereas subscript 3 marks the final BH, which results from a merger of 1 and 2 black holes.

2. Collapsing star with a companion black hole

2.1. Model of a BH surrounded by a torus

First, we test the predictions of the model of the collapsing star that encounters a companion BH. We use a simple “toy model” calculation to quantify the behaviour of the rotating BH in the center of the collapsing star and an accreting torus embedded in its envelope. We focus on the evolution of the BH spin and changes in the accretion rate within the torus, to make predictions on the duration and power available for the gamma ray burst.

The primary is a collapsing star, whose iron core has just formed a central BH of mass $M_{1,\text{init}}$. The distribution of density in the envelope is the same as used in Janiuk et al. (2008), and is taken from the spherically symmetric pre-supernova star of a mass of 25 $M_\odot$ (Woosley & Weaver 1995). The size of the star is $R_{\text{out}} \approx 6 \times 10^{13}$ cm, so the free-fall timescale from this radius is about $\tau_{ff} \approx 10^7$ s. The rotation of the stellar envelope leads to formation of the torus, i.e., high angular momentum shells located in the equatorial plane, that will subsequently accrete onto the core. The specific angular momentum distribution is in general given by

$$l_{\text{spec}} = l_0 f(\theta) g(r),$$

where the normalization is scaled to the critical angular momentum, $l_0/l_{\text{crit}} = x$. We express $l_{\text{crit}}$ as

$$l_{\text{crit}} = \frac{2GM_1}{c} \left(2 - a_1^2 + 2\sqrt{1-a_1^2}\right),$$

where $a_1$ is the primary black hole dimensionless spin parameter. The above equation gives the condition for the formation of a disk with the angular momentum exceeding that of the marginally bound orbit (Bardeen et al. 1972). The dependence on polar angle $\theta$ is

$$f(\theta) = 1 - |\cos \theta|. \quad (3)$$

In the present model we neglect the radial dependence, i.e., we take into account differential rotation only (see however Janiuk & Proga 2008 for the discussion of other rotation laws).

Both mass and spin of the primary BH change during the collapse of the envelope, as the massive shells accrete onto the center. The BH absorbs only the angular momentum of the gas, which is smaller than the critical one. The rotating torus, however, is supported by the gas which angular momentum is larger than the critical. The value of $l_{\text{crit}}$ changes during the collapse, affecting the evolution of the BH spin and conditions for the torus existence.

We then introduce a secondary (companion) BH of a mass $M_2$ and negligible spin, falling into the envelope of the primary star at the onset of its collapse. As the companion BH moves from the radius $r$ to $r - \Delta r$ inside the envelope, it transfers its specific orbital angular momentum to the shells:

$$\Delta l = \frac{dJ_2}{dr} = \frac{dM}{dr} \frac{dM}{dr} \approx \frac{M_2}{2} \frac{GM_2}{M(r)} (1 + \ln \frac{r_2}{r}),$$

where $M(r)$ is the mass of the envelope inside the radius $r$. We assume here that the companion BH orbital angular momentum is Keplerian, $J_2 = M_2 \sqrt{GM_2 r}$ (see Barkov & Komissarov 2010). In addition, we assume explicitly that the companion enters the envelope close to the equatorial plane, so that the specific angular momentum is transferred as $l_{\text{spec}} = l_{\text{spec}} + \Delta l f(\theta)$.

2.2. Homologous accretion without mass loss

First, we analyze the simplest scenario, where the whole envelope collapses via homologous accretion of subsequent shells. Therefore not only the high angular momentum, but also the low $l_{\text{spec}}$ gas contributes to the black hole evolution.

Fig. 1 shows the evolution of the BH spin with time. The time is calculated as a free-fall time of the envelope shell that surrounds the central BH of mass $M_{\text{BH}(t)}$. We show two examples of the specific angular momenta of the envelope, parameterized by $x = l_{\text{spec}}/l_{\text{crit}} = 1.5$ (solid lines) and $x = 7.0$ (dashed lines).

Initially, the BH spin grows in a short timescale due to accretion of high angular momentum material from the rotating torus. After it decreases, sometimes even below the initial value. This is due to accretion of the low angular momentum gas, i.e., with $l_{\text{spec}}$ smaller than the critical value $l_{\text{crit}}$ for a current BH mass and spin (Janiuk et al. 2008). If the spin-up of the envelope is neglected, the rotationally-supported torus is present only temporarily. Here however, the companion spins up the envelope again, so that the high angular momentum gas is available to spin up the primary BH. Finally, the furthest shells of the envelope collapse onto the center. The duration of this episode is not sensitive to the initial BH spin and angular momentum normalization. The latter affects the minimum spin of the pri-
mary BH during this episode, and in our examples it is about \(a_{1,\text{min}} = 0.4 - 0.5\) for \(x = 1.5\), and about \(a_{1,\text{min}} = 0.9 - 0.95\) for \(x = 7.0\). In any case, at the end of the collapse the primary BH will spin at almost maximum rate.

Our calculations show two accretion episodes. The first lasts up to a few hundreds of seconds, depending on angular momentum in the envelope, \(x\), and the primary BH spin \(a_{1,\text{init}}\). The accretion rate in the torus is initially almost \(0.1 \, M_{\odot} \, \text{s}^{-1}\) but steeply decreases, following the density profile of gas in the subsequent shells of the envelope. The second accretion episode begins at \(~ 500\) seconds and is governed by the presence of the companion. This episode lasts until the whole envelope has collapsed; the accretion rate (estimated simply as \(\Delta m_{\text{torus}}/\Delta t\)) now rises to above \(1 \, M_{\odot} \, \text{s}^{-1}\), because of larger mass available in the shells.

### 2.3. Torus accretion with mass loss

In the above section, the accretion rate was estimated using the free-fall timescale. Primary BH was spun up to a maximum rotation, practically regardless of its initial spin. Moreover, the homologous accretion of shells led to effective increase of the BH mass and at the end of the simulation it simply equals to the initial mass of the pre-collapse star.

Now, we consider a more realistic scenario, when accretion onto the primary BH proceeds through a thick, viscous disk and a substantial fraction of the envelope mass is not accreted but lost to the massive winds. Such winds were discussed in MacFadyen & Woosley (1999) and have also been found in numerical simulations by McKinney (2006), who reported on their mildly relativistic velocities and intermediate opening angles. In our recent work (Janiuk et al. 2013; Janiuk & Moscibrodzka 2012), we also studied the neutrino cooled disk/winds in the GRB central engine, via the magnetohydrodynamical simulations of accretion. We found that the mass taken away by the winds and not accreted onto the black hole through the event horizon might reach the fraction of even 50-72%. This fraction depends on the parameters such as black hole mass and spin, and might also be sensitive to the adopted initial distribution of the specific angular momentum in the gas. These winds are launched by the magnetic pressure and are bright in neutrinos that cool the central engine. We checked that for some models the winds appear to be bound, so that they would actually result in some large scale circularization movements, however for other models the wind velocity exceeds the escape velocity. The mass loss of 72% must therefore be treated as an upper limit.

Here, we assume a fiducial value of a maximum fraction of the wind mass loss, so that the mass accreted onto the primary BH is 28% of the shell, the remaining fraction being lost from the system.

The viscous timescale in the accretion disk is given by

\[
\tau_{\text{visc}} = \frac{250 \, \alpha \, \delta \, r_{g}}{0.01} \left( \frac{r}{10 \, r_{g}} \right) \left( \frac{M_{\text{BH}}}{10 M_{\odot}} \right) \text{s},
\]

where \(\alpha\) is the viscosity parameter, and \(M_{\text{BH}}\) and \(r_{g}\) are the BH mass and gravitational radius, respectively. The ratio of disk thickness to radius \(h/r \equiv \delta\) can be estimated from the model of a neutrino cooled disk in the GRB central engine (Janiuk & Yuan 2010); it is about 0.1 – 0.3 for the neutrino transparent (low accretion rate) models.

In the Figure 2 we plot the BH mass, accretion rate and BH spin as a function of time. The time is expressed in viscous time scales of the accreting torus at the distance \(r\) from the center. The final BH spin in this model is always maximal and is reached very quickly after the onset of accretion. In this scenario, most of the envelope’s mass is blown out with the wind and not accreted onto BH, while some of the matter is accreted but it contributes to the primary black hole spin up more than to its mass increase. We assume that 72% of the envelopes’ mass was ejected with the wind outflow. The mass of the central BH grows as long as the torus exists. The torus is supported by both the specific angular momentum in the envelope and by the companion. For the smallest \(t_{\text{esc}}\) normalizations we have tested, \(x = 1.5\), and no companion, we obtained \(M_{1,\text{final}} = 4.4M_{\odot}\) at the end of the simulation (the result is for the particular pre-collapse star density distribution and depends on the assumed fraction of the torus mass taken out by the wind). If no wind outflow was assumed, and the whole torus mass was accreted onto the BH, then its final mass was \(M_{1,\text{final}} = 8.4M_{\odot}\). This value is very weakly dependent on the angular momentum distributions in the stellar envelope.

We calculate the instantaneous accretion rate (middle panel of Fig. 3) in the torus as the ratio between the mass of an accreting shell and the local viscous timescale, \(\dot{m} = \delta m_{\text{torus}}/\delta \tau_{\text{visc}}\). Initially, the accretion rate is peaking at about \(0.01 \, M_{\odot} \, \text{s}^{-1}\) for a large specific angular momentum in the envelope. The second peak in the accretion rate lasts much longer, but the accretion rate is less than during the first peak, because of a smaller density of the accreted material. Finally, the accretion rate drops below \(10^{-4} \, M_{\odot} \, \text{s}^{-1}\) even though the torus persists, because of smaller density and long viscous timescale.

The accretion in the torus proceeds through three episodes, as shown in Fig. 3. The Figure shows the mass of a given accreting shell versus the free-fall timescale at the initial distance.
that 28% of the stellar envelope is accreted onto the BH, and the free-falling timescales below of this shell. The shells that are closest to the center, have their subsequently will accrete the outer shells. In our model, this moment corresponds to the distance of \( r_2 = 10^{11} \) cm and the free fall timescale at this distance is \( t_{\text{final}} \sim 530 \) s (scaling with mass \( M_1 \)).

In the homologous accretion scenario, the primary black hole mass is at this moment equal to about \( M_{1,\text{final}} = 9M_\odot \) (for our assumed progenitor star model, but independently on the initial core rotation rate and specific angular momentum distribution in the envelope). If the initial spin was \( a_{1,\text{init}} = 0.5 \), it temporarily dropped due to the in-fall of low angular momentum material, and then increased. The final value of the spin, for a moderately rapid rotation in the envelope, given by our parameter \( x = 3 \), was about \( a_{1,\text{final}} = 0.69 \).

This primary BH will then merge with the companion and we assume its mass of \( M_2 = 3M_\odot \) and negligible spin. After the merger, the remaining mass of the envelope, which in this example will be equal to about \( M_{\text{env,final}} \sim 16M_\odot \), will accrete onto the product of the merger.

The second scenario is the accretion through the viscous, rotationally supported torus onto the primary BH, under the assumption that most of the material is blown out with a massive wind. We assume that only 28% of mass accretes onto the core and contributes to its growing mass and spin. The resulting BH will nevertheless be spinning at the maximum rate, as all the accreting material has large specific angular momentum. The mass of the primary BH after this accretion episode is about \( M_{1,\text{final}} = 3.8M_\odot \). As the companion BH mass is again assumed 3 \( M_\odot \), the final BH is produced of a merger of two comparable mass BHs. The product \( M_3 \) subsequently accretes the remaining envelope. The mass of the gas available for accretion in the final episode is in this example equal to about 6\( M_\odot \).

In both scenarios outlined above, the mass of the final BH, \( M_3 \), and the remaining torus mass are comparable. We do not follow here this final accretion process numerically, as it would require an enormous computational power to run a full GR MHD simulation in a non-stationary metric. In the stationary Kerr metric, such simulations of accretion onto a single black hole have recently been shown elsewhere (e.g. [McKinney et al. (2012)]). We aimed however to treat in more detail the binary black hole merger process, which timescale is much shorter than the timescale of accretion of the distant torus, and may be treated separately from the surrounding matter, i.e. in the vacuum approximation. Below we present our several numerical simulations, focusing in particular on the two distinct scenarios that led to different initial parameters of the merging black holes.

### 3. Binary black hole merger

#### 3.1. Physics of the model

The simulation covers the very last stage of the evolution of binary BH system, when the separation of the components becomes so small, that the phases of inspiral, merger and ringdown can be tracked. This is the stage of the evolution for which the full set of Einstein equations needs to be solved numerically to model the geometry of spacetime in order to obtain reasonable results.
The initial state of the system under consideration consists of two black holes in quasi circular orbits with mass ratio varying from 2 to 3. The more massive black hole carries also spin perpendicular to the orbital plane, the second component is spinless. The direction of the initial spin vector of the black hole coincides with the direction of the orbital angular momentum of the binary system.

We performed several runs of simulations, for different values of spin of the rotating black hole. The parameters for each run are presented in Table 1. The initial separation of components is the same for each run and is equal to 6M, where the value of M is close to the ADM mass of the whole system (Arnowitt et al. 1959), defined as the mass measured by a distant observer in an asymptotically flat space time.

Despite the fact that we do not change mass parameters of punctures representing black holes (for numerical details see next section) for each run, the ADM mass of the system varies, since we vary the spin which contributes to the total ADM mass. This is a known property of rotating black holes, for example for analytical Kerr solution we have:

\[ M_{\text{ADM}} = \sqrt{M_{\text{irr}}^2 + \frac{S^2}{4M_{\text{irr}}^2}} \]

where \( M_{\text{ADM}} \) is the ADM mass, \( S \) is the spin of black hole and \( M_{\text{irr}} \) is the irreducible mass - namely the mass related to the area of event horizon (the mass of nonrotating black hole with the same area of event horizon, for more details see Misner et al. (2003)).

3.2. Numerics

We use the fifth release of the Einstein Toolkit\(^1\) (Löffler et al. 2012) based on Cactus Computational Toolkit (Goodale et al. 2003).

The initial data are provided by the TwoPunctures thorn (Ansorg et al. 2004). This module solves numerically the binary puncture equations for a pair black holes (Brandt & Brügmann 1997). The initial state of space time is described by extrinsic curvature in the Bowen-York form (B Bowen & York 1980), for given mass, momentum and spin of each puncture. These are the controlled parameters in the first section of Table 1.

The evolution is performed by the McLachlan module (Brown et al. 2009) which is a numerical implementation of the 3 + 1 split of Einstein equations, solving the Cauchy initial value problem using the Baumgarte-Shapiro-Shibata-Nakamura (BSSN) method (Shibata & Nakamura 1995). The simulation is performed on the cartesian grid with the size of 60 × 60 × 60M and resolution of \( dx = dy = dx = 2M \) (runs R1 - R7 in Table 1), or the size of 48 × 48 × 48M and resolution of \( dx = dy = dz = 1.6 \) (runs R8 and R9). We use 7 levels of the adaptive mesh refinement in two regions around singularities. Each refinement is by the factor of 2 and the radii of refinement regions are: 0.5, 1, 2, 4, 8 and 16 around each singularity. The regions of refined grid follow the positions of singularities (Schnetter et al. 2004). We assume that the space time has a reflection symmetry with respect to the plane spanned by the initial momenta of components of the BH binary system, which reduces the number of grid points by the factor of two. The apparent horizons are localized around the components of the BH system and around final merged black hole after it forms (Tilman 2004). The proper integrals over the isolated horizons are calculated to extract the values of mass and spin of the merged black hole (Dreyer et al. 2003).

In all simulations we note the effect of gravitational recoil of the final BH. This effect is illustrated in Fig. 4. This is known effect, see for example Tichy & Marronetti (2007). The calculation of the exact value of the recoil speed requires the evaluation of the momentum carried away by the gravitational radiation during the merger. We did not analyze the gravitational radiation in the first series of simulations performed. In order to estimate the recoil speed we have done last run of the simulation (R9 in the Table 1) once again with analysis of radiation included. To calculate total momentum carried by radiation we have followed algorithm described by Alcubierre (2008). We use the formula for \( dP/dt \) in terms of coefficients \( A^m \) of multipole expansion of the Weyl scalar \( \Psi_4 \). The coefficients \( A^m \) are computed by the thorns Wey1Scalar4 and Multipole on the sphere of radius 22M and \( l \) ranging from 2 to 4. We integrate \( dP/dt \) over the time of the simulation to get total linear momentum radiated from the system through gravitational waves. Since total momentum has to be conserved we are able to compute recoil of the merged black hole.

3.3. Results

Results of the simulations are presented in Table 1. We also present a plot of the BH trajectories for the run R9 (Fig. 4). We note that there is a saturation of the final BH spin at about \( a_1 \approx 0.8 \), (primary BH has \( a_1 = 0.9 \), and companion BH \( a_2 = 0 \) in all runs). Models with \( a_1 = 0.9 \) do not result in a significant growth of the final BH spin.

In the last five simulations (R6-R10) the initial momentum of the BH system was varied. The initial spin parameter \( a_1 \) was kept constant, \( a_1 = 0.9 \) in runs R6-R9. These initial data correspond therefore to orbits that are not necessarily circular. The values the final BH spin do not change significantly with the initial orbital angular momentum of the system. This can be understood as a manifestation of the emission of gravitational waves: part of angular momentum is radiated away with the gravitational radiation. Above a certain limit, the increase of the total angular momentum of the initial system (orbital and spin) does not result in the increase of spin of the final BH; the amount of angular momentum radiated away increases, however.

We have done quantitative analysis of gravitational radiation for the last two runs of simulations (R9 and R10 in the Table 1). The direction of the recoil is irrelevant, since it depends on which phase of the last orbit the components of the system meet (in our simulations must remain in the orbital plane, since the reflection symmetry is assumed). The velocity of the final BH depends on spins and masses of the components and basically it is on the order of a few thousands km/s (see, e.g. Tichy & Marronetti (2007)). In this particular cases we obtained the values of recoil speeds to be approximately 200 km/s and 300 km/s, for the runs R9 and R10, respectively.

The runs that roughly correspond to the pre-merging scenarios outlined in Section 2, are R5 or R9 for the first (i.e. homologous accretion) scenario and R10 for the second (i.e. torus accretion and wind outflow) scenario. The second one, being more realistic in the physical collapse models, leads to the approximately equal mass ratio of the merging holes and high spin of the primary. Our merger simulations confirm therefore, that a high recoil velocity is obtained in this case, albeit not as large as in the runs with black hole mass ratio of about 3 and moderate or high spins.
The primary BH is spun up to the maximum rotation rate due to accretion of only the high angular momentum material, while it accretes a moderate amount of mass only. Our calculations show, that the mass of the BH increases from 1.7 up to 3.8 $M_\odot$. It then merges with the companion BH of mass $M_2 = 3 ~M_\odot$. In the second scenario, the primary BH accretes both high and low angular momentum material from the envelope in the first stage. Therefore its mass prior to the binary BH merger is large, e.g., 9.2 $M_\odot$. The spin however may not increase significantly and even drop below the starting value. The details depend on the magnitude of specific angular momentum deposited in the stellar envelope. For our testing parameters, we obtained $a = 0.40$, $0.69$ and $0.94$ for the $l_{\text{spec}}$ normalizations $s = 1.5$, $3.0$ and $7.0$, respectively.

We found no significant dependence of our results on the companion mass, provided it is a stellar mass BH on the order of 1-3 $M_\odot$. In all the cases, we neglected the spin of the companion BH, as well as the increase of its mass in the Bondi-like accretion during its passage through the primary's envelope. Prior to the merger of the binary BH system, in the central engine we have either a maximally spinning and moderately massive, or more massive and moderately spinning BH and circumbinary torus. After the merger, the final BH mass is between $M_3 = 7 - 12 M_\odot$ and the mass of the remnant torus is about 16 $M_\odot$. We may expect that most of this material will eventually be lost from the envelope through the massive outflows. The transfer of the orbital angular momentum from the companion to the envelope leads to the longer lifetime of the rotationally supported torus around the primary BH. The accretion rate through this torus is small, however the infalling matter contributes to increasing BH mass and spin.

In the present work, we consider a fiducial value of the mass loss parameter from the accreting torus due to the powerful winds. Kumar et al. (2008) discuss the problem of mass fallback in the long GRB central engine and notice that the advection dominated part of the accretion flow generates a strong mass outflow. In their model, the 14 Solar mass star ends up with the black hole of 10 solar masses, which means that 4 solar masses (28 per cent) was lost from the system through the wind. Lindner et al. (2010) in their hydrodynamical simulations of collapsar use also the 14 Solar mass Wolf-Rayet star with low metallicity (of 0.01 Z⊙), which results in a very small mass loss. These authors use the radius dependent angular momen-

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### Table 1. Summary of the binary BH merger models. Parameters $m_1$, $p_1$, $m_2$, $p_2$ are mass and $x$-component of momentum of the primary and the companion BH, respectively. $s_1$ is the spin of the primary BH (the $z$-component). ADM values of the initial state are computed from the given controlled parameters: $M_1$ and $M_2$ are the ADM masses of the components, $M$ is the total ADM mass of the system, $a_1 = s_1/M_1^2$ is the dimensionless spin parameter of the first component. Final state $M_3$ and $a_3 = s_3/M_3^2$ are ADM mass and dimensionless spin parameter of the final BH.

| Run | $m_1$ | $m_2$ | $p_1$ | $p_2$ | $s_1$ | $M_1$ | $M_2$ | $M_1/M_2$ | $M$ | $a_1$ | $M_3$ | $a_3$ |
|-----|-------|-------|-------|-------|-------|-------|-------|------------|-----|-------|-------|-------|
| R1  | 0.632 | 0.316 | -0.121| 0.121 | 0     | 1.662 | 0.338 | 1.93       | 1.93| 0.576 | 0.989 | 0.226 |
| R2  | 0.632 | 0.316 | -0.121| 0.121 | 0.1   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R3  | 0.632 | 0.316 | -0.121| 0.121 | 0.3   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R4  | 0.632 | 0.316 | -0.121| 0.121 | 0.5   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R5  | 0.632 | 0.316 | -0.121| 0.121 | 0.7   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R6  | 0.632 | 0.316 | -0.121| 0.121 | 0.9   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R7  | 0.632 | 0.316 | -0.135| 0.135 | 0.9   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R8  | 0.632 | 0.316 | -0.16  | 0.16  | 0.9   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R9  | 0.632 | 0.316 | -0.172 | 0.172 | 0.9   | 0.666 | 0.338 | 1.97       | 1.97| 0.989 | 0.226 | 0.972 |
| R10 | 0.54  | 0.445 | -0.138 | 0.138 | 0.5   | 0.6   | 0.445 | 1.35       | 1.35| 0.788 | 0.982 | 0.779 |

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4. Discussion and conclusions

The scenarios presented here consider the long gamma ray burst case, resulting from the massive rotating star collapse that occurs in a close binary system with a companion BH. The event can be divided into three stages. First, the innermost shells of the massive primary accrete onto the core that has collapsed to a BH. These massive shells add the mass and angular momentum to this newly-born BH, and the ultimate outcome depends on the fraction of envelope that is blown away from the system through the wind. The companion BH spins up the outer shells of the rotating envelope and subsequently falls into the gap after the inner torus has been accreted. The second stage consists of the merger of two BHs, surrounded by a remnant circumbinary disk. The product of the merger will have a net spin and a recoil velocity that depends on the binary parameters. In the third stage the final BH accretes the remaining material that constitutes the outer rotationally-supported torus.

We studied two classes of models: with and without the massive wind launched from the primary star. In the first scenario, $9.2$ $M_\odot$. The spin however may not increase significantly and even drop below the starting value. The details depend on the magnitude of specific angular momentum deposited in the stellar envelope. For our testing parameters, we obtained $a = 0.40$, $0.69$ and $0.94$ for the $l_{\text{spec}}$ normalizations $s = 1.5$, $3.0$ and $7.0$, respectively.

Fig. 4. Trajectories of the component BHs for an exemplary simulation described in Table 1 (run R9). Simulation covers the last two orbits of BH binary (red and green) and the formation of the final BH (blue).
tum profile \( (r) \sin^2(\theta) \) with the magnitude at 3/4 mass radius of \( 8 \times 10^{17} \text{ cm}^2 \text{s}^{-1} \). In the models discussed in Janiuk et al. (2013), on which the fiducial value of the wind parameter was assumed here, the specific angular momentum was about \( 6 \times 10^{16} - 2 \times 10^{17} \text{ cm}^2 \text{s}^{-1} \) and therefore the centrifugal force could help driving the wind outflow. However, as we included also the magnetic fields and neutrino emission in those calculations, the more powerful winds were launched. Still, in not all models the winds appeared to be gravitationally unbound, therefore this fiducial number we assumed in the present paper must treated as an upper limit for the wind mass loss. Nevertheless, we note that the results presented in Section 2 are mostly sensitive to the adopted accretion scenario (i.e. the homologous vs. torus accretion) and the assumed wind fraction in case of torus accretion does not affect them in a great detail.

As for the progenitor star and its mass loss rate due to the wind, the rate is uncertain and observationally poorly constrained. Heger et al. (2003) found that a low metallicity reduces mass loss in supernovae (see also Woosley & Heger, 2006). Mapelli et al. (2013) use the power-law dependence of mass loss rate \( M \dot{Z}^\nu \), where \( \nu = 0.5 - 0.9 \) is the index for the main sequence stars. However, in case of Luminous Blue Variable stars and Wolf-Rayet stars this scaling might be different (Vink & de Koter 2005, Dwarkadas 2013) study the supernova remnants and find that the mass loss and wind velocities in the Wolf-Rayet stars are on the order of \( 10^{-5} M_\odot \text{yr}^{-1} \) and 2000 km s\(^{-1}\), respectively. In case of red supergiants, the mass loss rate is larger, but the wind velocity is smaller.

Observationally, at least some long GRBs that are associated with supernovae, must have strong winds which make them not ‘failed’ supernovae. These are e.g. GRB021211 (Della Valle et al. 2003). On the other hand, GRB 060614, 100 seconds long duration, had no supernova signatures (Della Valle et al. 2006).

The merger of two black holes occurs when the inner torus has completely accreted onto the primary and a clean gap formed at the distance of approximately twice the orbital separation (see, e.g., Shi et al. 2012, Farris et al. 2011a). For stellar mass BHs the timescale of the merger is of the order of milliseconds. The merger event in our simulations should occur at about \( 1700 - 2000 \) years, which is related to the timescale of the progenitor star collapse and the crossing time of the secondary component through the outer envelope shells. Accretion after the merger proceeds then onto the product BH, with a smaller accretion rate than in the first episode. This is because despite a large mass of the outer envelope shells, most of it is blown out and not accreted, while the viscous timescale at large radii is long. The total duration of this phase is determined by the size and mass of the primary star. In our model, the parameters of the star taken for a simulation imply the viscous timescale at \( t_{\text{esc}}(R_\text{esc}) \approx 10^2 \) s. This is therefore the source of a resulting GRB afterglow emission, observable at lower energies for the following few months after the prompt event.

The total observed event should have two distinct components in the electromagnetic signal, separated by a gravitational wave emission. One of the accompanying effects will also be the product black hole recoiled due to the gravitational waves. This effect has been intensively discussed recently for the scenarios of the supermassive black hole mergers. For instance, Bogdanović et al. (2007) proposed a scenario of gas-rich binary black hole mergers. In this scenario, torques from gas accretion align the spins of two black holes and their orbital axis with the large-scale disks. The authors argue, that this alignment prevents large kicks from the gravitational radiation recoil and helps explain the observations that ubiquity of black holes remain in the galaxy cores, despite their past mergers.

This reasoning is based on the results of the simulations. For instance, Baker et al. (2008) modeled the coalescence of non-spinning black holes with different mass ratios. Also, Gonzalez et al. (2007) and Campainelli et al. (2007) studied the cases with general spin orientations. These simulations show that for mergers with BHs of low spins or the spins aligned, the maximum speeds of the kick are below 200 km/s. For the spins oppositely directed and large \( \alpha \) values, the kicks exceed 4000 km/s, while the escape speed from the galaxy core is below 1000 km/s (Merritt et al. 2004). The simulations’ results are not conclusive to say however, that large kicks are prevented by the coaligned spins of merging black holes. For instance, Tichy & Marronetti (2007) performed simulations of equal mass BHs with spins of \( \sim 0.8 \) and random orientations. They showed that all recoil velocities are large, between 1000 and 2000 km/s. Higher spins lead to even larger kicks. The kick velocity depends also on the mass ratio. Above-mentioned authors did not calculate this, but they expect that smaller kicks will be obtained for unequal mass case. This is consistent with analytical estimates presented in Bogdanović et al. (2007). In our simulations, the mass ratios and spins are approximately either (i) \( q = 0.3, a_1 = 0.9 \) and \( a_2 = 0 \) or (ii) \( q = 1.35, a_1 = 0.8 \) and \( a_2 = 0 \), so the ratio between the two kicks will be about 0.8 with this simplified formula. Therefore the kick of 200 km/s obtained in the first case (unequal masses) would scale up to about 250 km/s for the second case. We obtained only a kick of 300 km/s in model R10, which seems to be in a rough agreement with these analytical estimates, taking also into account some numerical uncertainties.

The escape velocities estimated for a sample of short GRBs’ host galaxies from Svensson et al. (2010) with median mass of \( M_{\text{host}} = 1.310^9 M_\odot \) and the 80% light radius of \( r_{\text{80\%}} = 3.3 \text{ kpc} \) would be about 2280 km s\(^{-1}\). It is therefore not possible that the merger product simulated in our models will leave the host galaxy. Such extreme kick velocities could however be obtained if both merger components had very large spins.

The gravitational wave emission is estimated at \( \lesssim 10\% \) of the rest mass-energy of the system; similar figures can be obtained using the analytic phenomenological formulae derived from numerical-relativity simulations by Barausse et al. (2012). Our simulation covers the merger phase only, and the resulting gravitational wave emission is of the order of a few per cent (see Table 1 for the ADM mass differences).

By analogy to our current understanding of a two supermassive BHs system residing in the centers of merging galaxies, we suspect that the interaction with the gas-rich environment will facilitate the transfer of the kinetic energy and orbital angular momentum from the binary system to the gas\(^2\). This should result in “speeding up” the inspiral and fewer orbits before the merger. However, at smaller distances the two BHs may be orbiting in a region relatively cleared of matter, surrounded by a circumbinary disk/torus and the accretion from it may temporarily increase the binary system angular momentum, possibly pro-

\(^2\) The observations of binary galaxies in the process of merging are at present still poorly sampled. The only source for which the orbital modeling finds a tight BH system, i.e., a sub-parsec solution is OJ287 (Valtonen et al. 2012). The other pairs of supermassive black holes are rather wide, with separations on the order of hundreds of parsec. Kormer, Biajarzewska & Jamnik (2011), and the indirect evidence for the presence of binaries comes mostly from their semi-periodic lightcurves or the observations of ‘wiggles’ in the radio jets, e.g., Xu & Komossa (2009). Therefore the observational tests of such scenarios are also limited.
longing the inspiral phase. The problem of exact GW signature from such system depends on many unknown factors, like the recoil received during the creation of a second BH and subsequent eccentricity of the orbit, as well as the details of the MHD interaction with matter, and deserves separate studies.

The electromagnetic emission can be divided into three phases. First one is related to the collapse of the progenitor star and creation of the primary BH, and its electromagnetic emission is of the order of the SN emission. Second stage consists of the tidal interaction of the binary BH system with the circumbinary accretion disk. Rescaling the exploratory work results of [Farris et al. (2011)] shows that for the binary of $\approx 10 M_\odot$ the luminosity is $\approx 10^{43}$ erg/s, much fainter than the third and final phase, which pertains to the collapsar scenario. In the case of substantial recoil, the final BH will drag the inner part of the disk out of the system, and the electromagnetic counterpart will be altered.

The progenitors of such systems are evolved binaries in star-forming regions, most likely similar to Cyg X-1 or Cyg X-3. The first system most likely contains a high mass black hole, while the latter shows significant contribution of stellar wind component. The compact star in Cyg X-3 might already be a small mass black hole (Zdziarski et al. 2013) or a neutron star that will eventually collapse to a black hole during the inspiral phase.

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