On the viability of neutron star black hole binaries as central engines of gamma-ray bursts

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ABSTRACT

I discuss three-dimensional SPH simulations of neutron star black hole (BH) encounters. The calculations are performed using a nuclear equation of state and a multi-flavor neutrino treatment, general relativistic effects are mimicked using the Paczynski-Wiita pseudo-potential and gravitational radiation reaction forces. Most of the explored mass range (14 to 20 $M_\odot$) has not been considered before in numerical simulations. The neutron star is always disrupted during the first approach after most of its mass has been transferred directly into the hole. In none of the analyzed cases episodic mass transfer is found. For the lower end of the mass range ($M_{BH} \leq 16 M_\odot$) an accretion disk of moderate density ($\rho \sim 10^{10} g cm^{-3}$) and temperature ($T < 2.5$ MeV) forms around the hole; the rest of the material forms a rapidly expanding tidal tail, up to 0.2 $M_\odot$ of which are unbound. For higher mass black holes ($M_{BH} \geq 18 M_\odot$) almost the complete neutron star disappears in the hole without forming any accretion disk. In these cases a small fraction of the star (between 0.01 and 0.08 $M_\odot$) is spun up by gravitational torques and dynamically ejected. None of the investigated systems of this study yields conditions that are promising to launch a GRB. While we cannot completely exclude that a subset of neutron star black hole binaries, maybe black holes with low masses and very large initial spins, can produce a GRB, this seems to happen—if at all—only in a restricted region of the available parameter space. I argue that the difficulty to form promising disks together with the absence of any observed neutron star black hole binary may mean that they are insignificant as central engines of the observed, short-hard GRBs and that the vast majority of the latter ones is caused by double neutron star coalescences.

Subject headings: black hole physics—hydrodynamics—methods: numerical—nuclear reactions, nucleosynthesis, abundances—gamma rays: bursts

1. Introduction

Neutron star binary systems have been recognized as potential central engines of gamma-ray bursts (GRBs) already two decades ago; they have been mentioned in Paczynski (1986) and Goodman et al. (1987) and discussed in more detail by Eichler et al. (1989) (for a more complete bibliography we refer to existing reviews, e.g. Meszaros 2002 or Piran 2005). Paczynski (1991) discussed systems containing a neutron star (NS) and a stellar mass black hole (BH) as a possible GRB engine. These days, compact binary systems are considered the ‘standard model’ for the subclass of short gamma-ray bursts, that last typically for about 0.3 s (Kouveliotou et al. 1993). While NSBH binaries are usually just considered to be a minor variation on the topic of double neutron star merger (DNS), it has been pointed out recently (Rosswog et al. 2004) that it is not obvious, that such a coalescence will automatically produce a hot and massive accretion disk around the hole. Therefore, its role for gamma-ray bursts needs further investigations. During the disruption process tidal torques are expected to eject material into highly eccentric, possibly unbound orbits. This debris is extremely neutron rich, $Y_e \sim 0.1$, and therefore (if ejected at appropriate rates) holds the promise to be one
of the still much debated sources of r-process elements (Lattimer and Schramm 1974 and 1976). Moreover, NSBH systems are generally considered promising sources for ground-based gravitational wave detectors such as LIGO (Abramovici et al. 1992), GEO600 (Luck et al. 2001), VIRGO (Caron et al. 1997) and TAMA (Tagoshi et al. 2001). It is worth pointing out in this context that there is a controversy about the rates at which NSBH mergers do occur. Bethe and Brown (1998) argued that NSBH should merge about an order of magnitude more frequently than DNS, while a recent study by Pfahl et al. (2005) comes to the conclusion that the number of NSBH systems in the Galaxy should be below 1 % of the number of double neutron star systems. The current observational status is that there are 8 observed DNS (Stairs 2004), while not a single NSBH binary has been discovered yet.

Neutron star black hole merger simulations have been performed by several groups. Janka et al. (1999) used a grid based hydrodynamics code together with a nuclear equation of state (EOS) and a neutrino leakage scheme to explore the role of these mergers in GRB context. Lee (2000, 2001) and Lee and Kluzniak (1999a,b) used smoothed particle hydrodynamics with polytropic equations of state to explore the sensitivity of the results on the adiabatic exponent of the EOS. Lee and Ramirez-Ruiz (2002) have analyzed the flow pattern within an accretion disk around a BH and, in a recent paper (2004), they included neutrino processes in their simulations. Setiawan et al. (2004) constructed disks around stellar mass black holes and followed their evolution including explicit viscosity, Rosswog et al. (2004) investigated the dynamics of the accretion process and the formation of a disk during the merger. Stellar mass black holes formed in core collapse supernovae are thought to be born with masses ranging from about 3 to 20 M⊙ (Fryer and Kalogera 2001). Numerical simulations have so far only explored black hole masses up to 14 M⊙ (Janka et al. 1999 and Lee and Kluzniak 1999a,b and Lee 2000, 2001 used black holes up to 10 M⊙, Rosswog et al. 2004 explored masses up to 14 M⊙). In this paper we will focus on black holes with masses ranging from 14 to 20 M⊙. The 14 M⊙ case has been explored previously (Rosswog et al. 2004) using the same microphysics but a purely Newtonian BH-potential and may therefore serve to gauge the effect of the Paczynski-Wiita pseudo-potential.

A simple estimate for the radius where a star around a BH is disrupted is the tidal radius, R_{tid} = \left( \frac{M_{BH}}{M_{NS}} \right)^{1/3} R_{NS}. As it grows slower with the black hole mass than the gravitational radius, it is expected that higher mass BHs will have more difficulties building up massive disks. It has to be stressed, however, that these simple estimates should only be used for qualitative statements as the detailed numbers are off by factors of a few. Therefore such estimates would lead to completely wrong predictions for the system dynamics.

2. Simulations

The calculations are performed with a 3D smoothed particle hydrodynamics code that has been developed to simulate compact objects (for details see Rosswog et al. 2000, Rosswog and Davies 2002, Rosswog and Liebendörfer 2003). Particular attention has been payed to avoid artifacts from the use of artificial viscosity, away from shocks artificial viscosity is essentially absent (Rosswog et al. 2000, Rosswog and Davies 2002). The set of hydrodynamic equations is closed with a temperature and composition dependent nuclear relativistic mean field equation of state based on the tables of Shen et al. (1998a, 1998b) that has been smoothly extended to the low-density regime (Rosswog and Davies 2002). Local cooling and compositional changes due to weak interactions are accounted for with a multi-flavor neutrino treatment (Rosswog and Liebendörfer 2003). The self-gravity of the neutron star material is calculated using a binary tree (e.g. Benz et al. 1990). The Paczynski-Wiita pseudo-potential is used to approximately take into account the presence of general relativistic effects around the black hole such as the presence of a last stable orbit. Clearly, the use of the Paczynski-Wiita potential is not a complete substitute for fully fledged general relativistic hydrodynamic simulation around a Schwarzschild black hole. It has, however, turned out to be astonishingly accurate: it provides the exact values for the last stable circular orbit (R_{isco} = 6 M_{BH}; G = c = 1 throughout this paper) and the marginally bound orbit (R_{mb} = 4 M_{BH}). Direct comparisons with general
relativistic solutions in a Schwarzschild space time show that the pseudo potential is able to capture the essentials of general relativity and can reproduce accretion disk structures to an accuracy of better than 10% (see e.g. Artemova et al. 1996). I restrict myself to initially corotating systems as the corresponding equilibrium configurations can be constructed accurately using the hydrocode itself (see Rosswog et al. 2004). The simulations presented here use up to $3 \cdot 10^6$ SPH particles and therefore are currently the best resolved models of neutron star black hole encounters (Rosswog et al. (2004) used up to $10^9$ particles, Lee (2001) used slightly more than 80000 particles).

The neutron star always has a mass of $1.4 M_\odot$ and a radius of 16 km, the black hole masses vary from 14 to $20 M_\odot$, see Table 1.

3. Results

The neutron star is always completely disrupted during the first encounter. In all of the cases a large portion of the neutron star is transferred directly into the hole without any accretion disk formation. The corresponding peak accretion rates exceed 1000 $M_\odot$/s for about 1 ms, after this short episode they drop by at least two orders of magnitude, see panel one in Figure 1.

It is instructive to compare the 14 $M_\odot$ case to the corresponding case of our previous study (Rosswog et al. 2004), where we had used a Newtonian BH potential. In the purely Newtonian case we found episodic mass transfer with a low-mass, “mini neutron star” surviving throughout the whole simulation or about eight close encounters. In the Paczynski-Wiita case about 1.15 $M_\odot$ (see panel two in Figure 1) are transferred directly into the hole, the rest forms a rapidly expanding tidal tail. The tidal tail still contains an outward-moving density maximum (corresponding to the mini neutron star of the Newtonian case), but its self-gravity is not strong enough to form a spherical object. The motion around the hole always has a strong radial velocity component and is far from being Keplerian. The matter fraction that is not swallowed during the first orbit collides with the accretion stream forming a spiral shock (see Figure 2). In this shock the temperatures slightly exceed 2 MeV, the other disk regions are substantially colder. The disk is substantially diminished on timescales of a few orbital periods. The densities never exceed $6 \cdot 10^{10}$ g cm$^{-3}$, the neutrino luminosities reach peak values of only $2 \cdot 10^{50}$ erg/s and are thus about three orders of magnitude lower than in our simulations of neutron star binary mergers (see Rosswog and Liebendörfer 2003) where the same microphysics was used. The results are well converged, runs I and II show excellent agreement in the BH masses and peak mass transfer rates. Some minor deviations are visible at low mass transfer rates (see panel one in Fig. 1 and the distance, $R_{MT}$, where numerically resolvable mass transfer sets in; see column six in Table 1). The case with 16 $M_\odot$ BHs behaves qualitatively very similar to the 14 $M_\odot$ BHs: about 1.2 $M_\odot$ are transferred into the hole, the disk is slightly less massive, hot and dense than the 14 $M_\odot$ case. Again, the two different resolutions yield nearly identical results.

The systems containing BHs of 18 $M_\odot$ or more (runs V and VI) do not form accretion disks at all. Almost the complete neutron star flows via the inner Lagrange point directly into the hole, only a small fraction of the star is spun up enough by tidal torques to be dynamically ejected, see last column in Table 1. In these cases the remnant consists of the black hole (without any accretion disk) and a rapidly expanding, concentric (half-)ring of neutron-rich debris material (0.08 $M_\odot$ for the 18 and 0.01 $M_\odot$ for 20 $M_\odot$ BH).

The ejected mass fraction found in these simulations is near the range estimated by Lattimer and Schramm (1974 and 1976), they estimated $0.05 \pm 0.05 M_\odot$. Our nucleosynthetic calculations for such debris material for the neutron star merger case (Freiburghaus et al. 1999) yielded excellent agreement with the observed r-process abundances from around Barium up to beyond the platinum peak. If large parts of the disrupted neutron star should form r-process material, a conflict with the observed element ratios in metal-poor halo stars might arise (Argast et al. 2004), if their coalescence rates are similar to those of double neutron stars (DNS). The problem is avoided if NSBH coalesce much less frequently than DNS. This would be consistent with the non-observation of any NSBH-system (currently 8 DNS systems are known, see Stairs 2004) and the result of recent studies (Pfahl et al. 2005) that estimate their number in the Galactic disk to be less than 0.1-1% of the number of DNS.
It is worth pointing out that in some of the investigated cases mass transfer sets in only at distances considerably smaller than $R_{\text{isco}}$ (e.g. run VI, see Table 1). This however, does not mean that the star is swallowed as a whole (keep in mind that $R_{\text{isco}}$ refers to the case without self-gravity and to circular motion; both conditions are not satisfied here). In the 16 M$_{\odot}$ BH case still a tidal tail and accretion disk forms, in the higher mass cases at least some material escapes from being drawn into the hole.

4. Discussion

We consider all the approximations made to be valid to a high degree. If an accretion disk forms at all (i.e. for the BH masses at the lower end of the explored range) it is of only moderate density ($\sim 10^{10}$ g cm$^{-3}$) and completely transparent to neutrinos. Therefore the neutrino emission results cannot be influenced by our flux-limited diffusion treatment. Moreover, the results are numerically converged, different numerical resolution yields for the gross properties almost identical results. The BHs are massive enough to dominate the spacetime completely and as they are spun up to spin parameters of only 0.2 (see Table 1), we consider the use of PW-potentials a very good approximation (note that for $a=0.2$ the event horizon moves from 2 to 1.98 and the last stable orbit from 6 to 5.33 gravitational radii).

None of the investigated NSBH systems yields disks that are promising as GRB engines. The disks formed in the low mass BH cases are relatively cold and of low density, the neutrino luminosities are more than two orders of magnitude below our results from the neutron star merger case (Rosswog and Liebendörfer, 2003). In the latter case the GRBs launched via $\nu\bar{\nu}$-annihilation were rather weak by GRB standards and, as the neutrino luminosities enter quadratically in the energy deposition rate, $\nu\bar{\nu}$-annihilation does not seem a viable GRB mechanism for the investigated NSBH systems. Due to the lower densities the magnetic fields that can be anchored in the disk are substantially lower that in the DNS case, whether they still can launch a GRB remains to be explored in the future. BHs beyond $\sim 18$ M$_{\odot}$ do not lead to any accretion disk formation at all and can therefore be ruled out as sources of GRBs.

We still cannot generally rule out NSBH-systems as central engines of GRBs. One might speculate, for example, about about an extremely high disk viscosity. Another possibility is the nuclear EOS. Our previous investigations (Rosswog et al. 2004) showed that the dynamics of the merger is sensitive to the EOS. Here, I used a relativistic mean field EOS with neutrons and protons as the only baryonic constituents of matter. This EOS is certainly on the stiff side of the possible range of nuclear equations of state. Maybe a substantially softer EOS could make the outcome of the merger more promising to launch a GRB. The possibly most robust way out, however, are BHs that are already from the beginning spinning very rapidly and that are spun up during the merger to values very close to the maximum spin parameter of $a = 1$. In this case both the position of the last stable orbit and the event horizon move to 1 M$_{\odot}$BH and thus closer to the hole. Therefore, much higher temperatures and densities might be reached in the inner disk regions.

It seems that a large part of the parameter space does not yield conditions that are promising to launch GRBs. This difficulty to form promising disks together with the absence of any observed NSBH system may mean that NSBH binaries are insignificant as central engines of the observed, short-hard GRBs and that the majority of the latter ones is caused by double neutron star coalescences. NSBH mergers may just manifest themselves as sources of gravitational waves and transient X-rays.

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Table 1: Summary of the different runs. $M_{BH}$: black hole mass; $q=M_{NS}/M_{BH}$; $R_{tid}$: tidal radius; $a_0$: initial separation; $R_{isco}$: last stable orbit Schwarzschild black hole; $R_{MT}$: distance where numerically resolvable mass transfer sets in; # part.: SPH particle number; $T_{sim}$: simulated duration; $a_{BH}$ is the dimensionless black hole spin parameter; $M_{ej}$ refers to the material that is dynamically ejected during the merger.

| run | $M_{BH}$ [$M_\odot$] | $M_{BH}$ [$M_\odot$] | $R_{tid}$ [km] | $a_0$ [km] | $R_{isco}$ [km] | $R_{MT}$ [km] | # part. | $T_{sim}$ [ms] | $a_{BH}$ ($T_{sim}$) | $M_{ej}$ [$M_\odot$] |
|-----|------------------|------------------|----------------|------------|----------------|----------------|--------|----------------|----------------|----------------|
| I   | 14/0.1           | 36.1             | 127.5          | 124.1      | 117            | 570587        | 34.6   | 0.196          | 0.20           | 0.20           |
| II  | 14/0.1           | 36.1             | 127.5          | 124.1      | 117            | 570587        | 34.6   | 0.196          | 0.20           | 0.20           |
| III | 16/0.0875        | 37.7             | 145.5          | 141.8      | 122            | 570587        | 78.1   | 0.197          | 0.15           | 0.15           |
| IV  | 16/0.0875        | 37.7             | 145.5          | 141.8      | 123            | 1005401       | 60.9   | 0.197          | 0.15           | 0.15           |
| V   | 18/0.0778        | 39.3             | 162            | 159.6      | 123            | 570587        | 50.4   | 0.201          | 0.08           | 0.08           |
| VI  | 20/0.07          | 40.7             | 187.5          | 177.3      | 128            | 1503419       | 179.6  | 0.198          | 0.01           | 0.01           |
Fig. 1.— Left panel: The mass transfer rates as a function of time. In one case (q=0.078, i.e $M_{\text{BH}} = 18 M_\odot$) the mass transfer stops completely. This is also true for the 20 $M_\odot$ case (not shown). Right panel: The growth of the black hole with time is shown for five of the runs. Note that the runs that simulate the same systems (run I and II; run III and IV) with different resolutions yield nearly identical curves.
Fig. 2.— Blow-up of the inner disk region of run II at \( t = 18.396 \) ms after simulation start (left panel: log(density); right panel: temperature). Clearly visible are the shock, where the accretion stream interacts with itself and strong decrease in the density inside the last stable orbit.