Relativistic Outflows From Remnants of Compact Object Mergers and Their Viability as Progenitors of Short Gamma-ray Bursts

M. A. Aloy
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany. and Departamento de Astronomía y Astrofísica, Universidad de Valencia, 46100 Burjassot, Spain.
T.-H. Janka, E.Müller
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany.

We summarize the most important results of a series of relativistic hydrodynamic simulations of mergers of compact binaries as potential candidates to be progenitors of short gamma-ray bursts. We discuss some of the generic conditions under which a short gamma-ray burst can be initiated and collimated in this kind of progenitor and the main characteristics of the resulting outflow. We conclude that not every merger will be able to produce a short gamma-ray burst. The generation of a successful event depends on the mass of the halo produced during the process of merging of the system. Due to the lateral structure of the generated ultrarelativistic outflows we expect some degree of variability between observed bursts, depending on the viewing angle relative to the system axis. Such differences will be superimposed on variations due to intrinsic properties of the binary systems and remnant BH-torus systems, e.g., associated with different masses and spins of the merging neutron stars or black holes.

1. INTRODUCTION

Due to their different duration and spectral properties Gamma-Ray Bursts (GRBs) are commonly divided in two classes: short-hard ($\leq 2\,\mathrm{s}$) and long-soft ($\geq 2\,\mathrm{s}$) GRBs [1]. A number of afterglow multi band observations (from radio to X-rays) of long GRBs have connected them to the same massive stars that are progenitors of Type I Supernovae [e.g., 2, 3]. Observations of short GRBs are less numerous and it has not been possible to detect them in multi frequency searches. Thus, progenitors of short GRBs are still rather unknown. A possibility is that these short bursts arise after the merger of a compact binary system [e.g., 4, 5]. Then, a few solar mass black hole (BH) forms, surrounded by a temporary debris torus whose accretion can provide a sudden release of gravitational energy. Once the thick disk is formed, up to $\sim 10^{51}\,\mathrm{erg}$ can be deposited above the poles of the BH in a region that contains less than $10^{-5} M_\odot$ of baryonic matter. The released energy must be able to accelerate the baryonic matter to ultrarelativistic speeds in order to produce a GRB event. If the duration of the burst is related to the lifetime of the system [6] this kind of events can only belong to the class of short GRBs because the expected time scale on which the BH engulfs the disk is fractions of a second [7].

In this work we summarize some of the findings of Aloy et al. [8] who address the question of whether a local deposition of energy above the accretion disk produced after the merger of two compact objects can yield the formation of a pair of relativistic, collimated plasma outflows in opposite directions that can account for short GRBs. Moreover, we want to study the mechanism by which the outflowing plasma can be collimated, the expected durations of the GRB events generated in this framework and whether these durations are related to the time during which the source of energy is active. Finally, we will provide some estimates of the expected rates of short GRB events and

2. NUMERICAL SET UP

We use the high-resolution shock-capturing code GENESIS [9, 10] to integrate the general relativistic hydrodynamic equations in spherical (r, θ) coordinates assuming axial symmetry. We have constructed two initial models in which the gravitational field is provided by a Schwarzschild BH of $3\,M_\odot$ (models type-A) and $2.44\,M_\odot$ (models type-B) located at the center of the system. These black holes are surrounded by thick accretion disks (which we assume to be non self-gravitating) for which the initial configurations are built as explained in Aloy et al. [8]. The initial models include an environment which is of high density and non uniform in type-A models. In type-B models it is spherically symmetric, with low density which decreases with radius ($\rho \sim r^{-3.4}$) and having a total mass of $2.52 \cdot 10^{-7}\,M_\odot$. We assume equatorial symmetry, and we cover 90° in the angular θ-direction with 200 uniform zones. In the r–direction the computational grid consists of 400 (type-A) or 500 (type-B) zones spaced logarithmically between the inner boundary and an outermost radius of $R_{\max} = 2 \cdot 10^{10}\,\mathrm{cm}$.

In a consistent post neutron star merger model an outflow will be powered by any process which gives rise to a local deposition of energy and/or momentum, as e.g., $\nu\bar{\nu}$–annihilation, or magneto-hydrodynamic processes. We mimic such a process by releasing pure thermal energy in a prescribed cone around the rotational axis of our system. In the radial direction the deposition region extends from the inner grid boundary located at $2R_g$ ($R_g = GM/c^2$; G, M and c being the gravitational constant, the mass of the BH and the speed of light in vacuum, respectively) to the outer radial boundary. In the angular direction, the half–opening angle of the deposition cone (θ_0) was chosen to be in the range $30^\circ - 75^\circ$. From the annihilation rate distribution computed in Ruffert & Janka [7] and Janka et al. [11], we infer a power law distribution for the energy deposited per unit of volume in the surrounding of the system whose explicit form was approximated as $\dot{q} \propto z^{-5}$, where z is the distance along the rotation axis.

3. RESULTS AND DISCUSSION

For energy deposition rates ($\dot{E}$) larger than a certain threshold $\dot{E}_{\rm th}$, all the models lead to either relativistic jets or ultrarelativistic winds (i.e., fireballs). The threshold is due to the need of overcoming the ram pressure $p_{\rm ram}$ that is exerted by the infalling external medium onto the new born fireball close to its initiation site. If the amount of energy per unit of volume pumped into the deposition region (in an interval of about of the free falling time of the fluid located at distances of the order of the radius of the torus) is not larger than $p_{\rm ram}$, the fireball is swallowed by the BH. The precise value of the threshold is model dependent because the densities and accretion velocities outside the thick torus depend on the details of the merger phase. For type-A models we find $\dot{E}_{\rm th} \sim 10^{49}\,{\rm erg\,s^{-1}}$, while for type-B models $\dot{E}_{\rm th} \lesssim 10^{48}\,{\rm erg\,s^{-1}}$. The smaller value in type-B models is due to their smaller ambient density.

Depending on the energy deposition rate and on the ambient density the outflows are either jets (i.e., outflows where the lateral boundaries are causally connected) having a very small opening angle ($\lesssim 8^\circ$) or relatively wide opening angle ($\lesssim 25^\circ$) winds (i.e., the lateral boundaries are not causally connected) or jets. Models close to the thresholds of the energy deposition rate or with a high density environment tend to form relativistic ($\Gamma \sim 10$), low density, knotty jets whose head propagates at mildly relativistic speeds($\sim 0.6c$). In contrast, models well above the threshold with dense environments or, independent of the deposition rate, in case of diluted environments either tend to form conical, ultrarelativistic ($\Gamma \gtrsim 400$) winds which are smooth, propagate at relativistic speeds ($\sim 0.97c$) and can be fitted by analytic power laws in case of models of type-A, or they propagate at ultrarelativistic velocities ($\gtrsim 0.9999c$; because there is much less mass in the ambient) being rather irregular due to the effect of large Kelvin-Helmholtz (KH) or shear driven instabilities [12] originating from their interaction either with the torus, or with the environment in case of type-B models. Indeed, the growth of KH modes determines whether the profiles of the physical variables are smooth and monotonically decreasing in the θ-direction (type-A), or non-smooth and non monotonic (type-B). The larger growth of surface instabilities in models of type-B is due to the larger density contrast with respect to the environment in these type of models. An effect of the KH instabilities is to entrain mass into the relativistic outflows of type-B models. The amount of entrained mass is comparable in both type of models.

The opening angle of the resulting outflow is set by the inertial confinement produced by a relatively high density medium in type-A models. In case of lower density environments, the complete collimation process happens in less than 1 ms (approximately, the light crossing time of the torus) and the opening angle of the outflow (θ_w) is set by the angle that the *walls* of the torus form with respect to the axis of the system (Fig. 1), and neither by the external medium (which is much more rarefied in type-B models), nor by the angular size of the deposition region (θ_0 in Fig. 1). When the energy deposition starts, due to its almost isotropic expansion, the newly born fireball impinges against the much denser torus and in the lateral boundaries of the outflow two discontinuities develop: a shock that sweeps up the torus and the external medium and a rarefaction wave in which the fluid is deflected towards the axis (at the same time that speeds up because of the density decrease in the rarefaction). Due to the on-going acceleration, by the time that the rarefaction reaches the axis, the Lorentz factor is $\gtrsim 10$ and the fireball lateral expansion is extremely reduced. We have checked [8] that in spite of the fact that there is a heavy, subrelativistic wind, driven (artificially) by the energy deposition, from the outer layers of the accretion disk, the ultrarelativistic outflows are not collimated by that wind as has been proposed by Levinson & Eichler [13].

Increasing the energy deposition rate yields an increase of the average Lorentz factor of the outflow at any given time. In models of type-A, the increase of $\dot{E}$ results in a transition in the outflow morphology from relativistic jets ($\dot{E} < 10^{51}{\rm erg\,s^{-1}}$) to ultrarelativistic wind-like outflows ($\dot{E} > 10^{51}{\rm erg\,s^{-1}}$). In models of type-B, we find ultrarelativistic winds for all energy deposition rates considered ($\dot{E} > 5 \cdot 10^{48}{\rm erg\,s^{-1}}$). For energy deposition rates leading to conical wind structures, θ_w ($\sim 20^\circ - 30^\circ$) is quite insensitive to $\dot{E}$ because the outflow opening angle is set by the inclination of the walls of the torus.

In type-A models, decreasing θ_0 produces a transition from narrow jets to wide angle winds. In type-B models there is almost no difference in the opening angle of the wind when we vary θ_0 between 30° and 75°. However, there is a slight decrease of θ_w and an increase of the mass entrained with increasing θ_0 because the energy deposition cone spans a larger volume of the accretion torus. In general, increasing

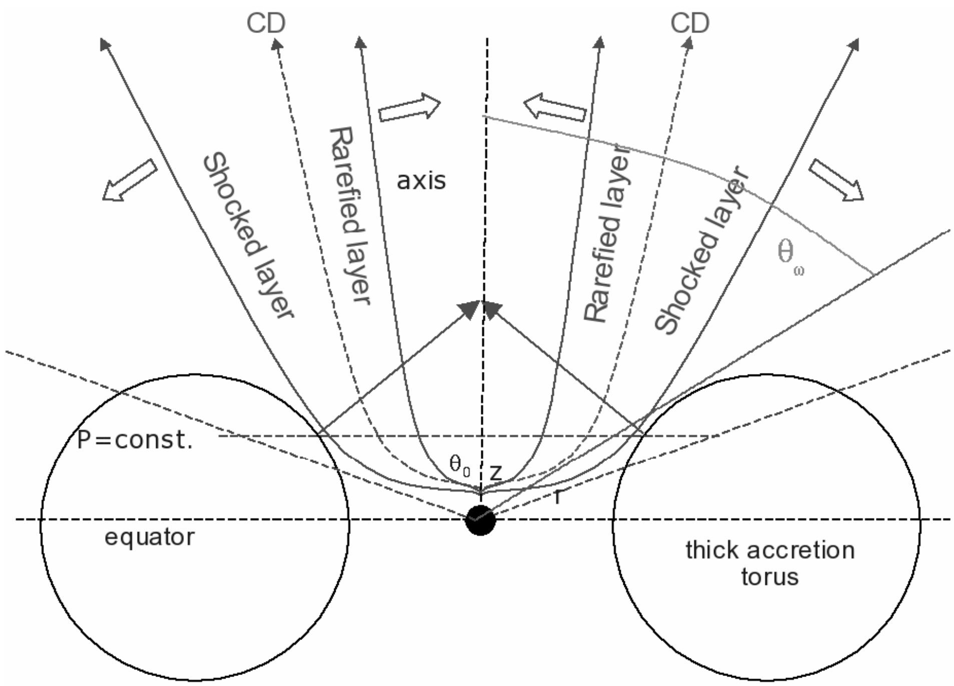

Figure 1: Scheme of the collimation process of the fireball produced after the merger of a compact binary system. The limits of the deposition region are marked by dashed lines. The empty arrows show the direction of propagation of each of the discontinuities that develop from the interface (i.e., the contact discontinuity; CD) between the fireball and the external medium. A shocked layer propagates away from the CD and sweeps up the external medium and the torus. A rarefaction wave propagates through the axis. The collimation is produced when the fireball impinges against the much denser torus and is deflected towards the symmetry axis.

θ_0 while keeping $\dot{E}$ constant leads to smaller average Lorentz factors in the resulting outflow.

We have followed the evolution of our models after the shut down of the energy deposition. It turns out that outflows propagating in high density environments (type-A) will not yield successful GRBs while most of the models with diluted environments (type-B) can do so. The reason being that, in type-B models, the environment is diluted enough to allow for the ultrarelativistic propagation of the leading edge of the fireball as required by the standard model of GRBs. The only exception to this rule happens when the half–opening angle of the deposition region is $\gtrsim 75°$ (model B03 in [8]), in which case the outflow blown by the energy release is too heavy to become ultrarelativistic. Type-A models sweep up more ambient mass than regular type-B ones and the leading front of the outflow slows down and it is eventually caught up by the rear edge of the outflow (this rear edge appears when the energy deposition is shut down and the fireball detaches from the inner boundary of the deposition region). Therefore, we conclude that not every merger may yield an observable short GRB event. The key parameter to produce an observable event is the mass of the halo generated during the merging epoch of the compact objects. Roughly, a mass of the halo $\approx E_d/c^2$ will prevent any ultrarelativistic outflow although other kind of observational signature might generate. We have estimated [8] that a low–luminosity ($\sim 10^{43}\,\mathrm{erg\,s^{-1}}$), soft UV-flash (with a typical temperature of $\sim 5\times10^4\,\mathrm{K}$) may be emitted as a result of the nonrelativistic outflow expanding from BH-tori systems in high–density merger halos. Due to the small luminosity predicted, only nearby events might be detectable.

The total energy (internal plus kinetic) of the relativistic fireball in type-B models scales roughly linearly with the deposited energy and saturates after the energy release has ended. A burst-like, short initial phase of energy deposition, followed by a long-time, gradual decay turned out to channel somewhat less energy into the relativistic outflow and to be slightly less efficient in converting internal energy to kinetic energy than a constant rate of energy release with a sudden end. In both cases a minor part (a few per cent at most) of the energy was in form of kinetic energy after 0.5 seconds of computed evolution, with the tendency to continue rising.

With a half-opening angle of $\theta_\mathrm{j} \sim 5°$–$10°$ ($15°$–$25°$) the collimated ultrarelativistic outflows of type-B models having $\Gamma \gtrsim 100$ ($\Gamma \gtrsim 10$) at $t = 0.5$ seconds after the onset of the energy release by the GRB engine, cover a fraction $f_\Omega = 1 - \cos\theta_\mathrm{j} \sim 0.4\%$–$1.5\%$ ($< 10\%$)

of the sky[1]. Assuming equal detectability from all directions within the opening angle this fraction implies about 100 (more than 10)[1] times more events than measured gamma-ray bursts. A rate of short GRBs of about 100 per year therefore requires an event rate per galaxy and year of $10^{-5}(f_\Omega/0.01)^{-1}(N_{\rm g}/10^9)^{-1}$ where $N_{\rm g}$ is the number of visible galaxies. Comparing with estimated NS+NS and NS+BH merger rates, which are typically around 10^{-5} per year and galaxy (with about a factor of 10 or more uncertainty; [e.g., 14, 15]), we therefore conclude that a significant fraction of such mergers but probably not all, should produce GRB viable outflows.

Of course, our rate estimate is very simplistic and neglects many important effects (e.g., the redshift distribution of mergers) which a more careful analysis must take into account [16]. Nevertheless, our numbers are in the ballpark of their results, and the conclusions are similar. Taking our computed jet opening angles for granted the analysis by Guetta & Piran [16] would also mean that not all compact binary mergers can produce GRBs. This in fact must even be expected, considering the special requirements for GRB suitable conditions, e.g., a baryon-poor environment around a black hole-torus system. If the merger remnant, for example, does not immediately or not at all collapse to a black hole (as is probably the case when two neutron stars with rather low masses merge, see e.g. Morrison et al. [17]), the rapidly spinning remnant will pollute its environment by a neutrino-driven wind. In this case a situation similar to our type-A models may result, i.e., the system will be enveloped by a dense, extended baryonic halo, and a GRB is disfavored.

The edges of the ultrarelativistic ($\Gamma > 100$) jet core in type-B models are very sharp in terms of the isotropic equivalent energy $E_{\rm iso}$. Maximum (terminal) Lorentz factors of the order of 1000 suggest the potential to account for hard GRB spectra. Our simulations actually showed inhomogeneous and anisotropic, collimated outflows with lateral variation of the Lorentz factor and of the apparent isotropic energy. Hence, we do not expect equal observability from all positions in the beam direction. The maximum values of the apparent isotropic energy, $E_{\rm iso}$, are found to be up to about 10^{51} erg at angles $\lesssim 10^\circ$ around the symmetry axis of the ultrarelativistic outflow, declining towards the outer wings of less relativistic ejecta. These numbers are obtained for an energy deposition rate of a few $10^{50}\,{\rm erg\,s^{-1}}$ over a period of typically 100 ms. These are reasonable and not extreme values in view of model calculations for the energy release by neutrino-antineutrino-annihilation in case of post-merging BH accretion [7, 11, 18]. Provided a major fraction of the energy of the ultrarelativistic fireball gets converted to gamma-rays, our maximum isotropic equivalent energies are in good agreement with estimates based on a comparison of the energetics of short and long GRBs, suggesting an approximate fluence-duration proportionality [19]. Since long bursts last typically about 50–100 times longer, a similar luminosity ([e.g., 20]; $L_{\rm iso}^{\rm short} \sim L_{\rm iso}^{\rm long} \sim 10^{51-52}{\rm erg\,s^{-1}}$) implies an apparent energy which is around 10^{51} erg for short bursts instead of $\sim 10^{53}$ erg for long ones [21].

Due to the lateral structure of the outflow we also expect some degree of variability between observed bursts, depending on the viewing angle relative to the system axis. Such differences will be superimposed on variations due to intrinsic properties of the binary systems and remnant BH-torus systems, e.g., associated with different masses and spins of the merging neutron stars or black holes. This finding should be taken into account in studies of the diversity of short gamma-ray bursts like the recent one by Rosswog & Ramirez-Ruiz [22]. These authors also employed the assumption that the ultrarelativistic outflow is confined as suggested by Levinson & Eichler [13]. Our models, however, show a much different hydrodynamic scenario for the fireball evolution and collimation, in which the outflow-torus interaction, relativistic shock effects, and Kelvin-Helmholtz instabilities play a crucial role. Therefore, conclusions based on grounds of the simplified picture developed by Levinson & Eichler [13] should be drawn with caution. Our results suggest that it is impossible to estimate the energetics of ultrarelativistic outflows without performing simulations that follow the complex hydrodynamics phenomena which develop in response to the deposition of energy in the vicinity of the BH-torus system. A static analysis of time slices for mass distribution and energy deposition by $\nu\bar{\nu}$-annihilation [e.g., 23] can therefore be misleading, in particular with respect to the outflow energetics and asymptotic Lorentz factor which are crucial for judging the viability of $\nu\bar{\nu}$-annihilation for powering GRBs.

We find that the larger the halo mass, the larger the baryonic contamination of the outflow. However, the matter entrained by the outflow does not distribute uniformly all over it but, instead, accumulates in a high-density, mildly relativistic cocoon around a central low-density, ultrarelativistic core (the central core becomes narrower as the entrained mass increases). Considering that type-A and type-B models span a broad range of environmental densities or halo masses, we can conjecture that mergers having halos with masses intermediate between those of type-A and type-B models may yield a number of different observational signatures between short GRBs and UV flashes. In particular, if the halo mass is slightly larger than that of type-B models, although a cen-

[1]The numbers in brackets correspond to outflow with Lorentz factors $\gtrsim 10$ at 0.5 s, which shows still ongoing acceleration so that much larger Lorentz factors can finally result

tral ultrarelativistic core might still be formed, most of the energy would be tapped into the cocoon surrounding such core. The observational signal associated to such events might display some similarities with that generated by, e.g., X-ray flashes. However, this prediction should be taken with caution and a more detailed analysis of the non-thermal emission of the ejected cocoons should be carried out before extracting firm conclusions.

Finally, in type-B models the fireball stretches substantially in radial direction, because the propagation velocity of its leading front is larger than its rear edge. In case that the GRB duration, $\Delta t_{\rm b}$, is defined by the time difference between the front and rear ends of the fireball reaching the *transparency radius*, e.g., 10^{13} cm, we can estimate, by extrapolating the results of our computed models, a burst duration $\Delta t_{\rm b}$ that might be significantly longer than the on-time (~ 0.1 s) of the source: $\Delta t_{\rm b} \cong 4.3^{+10.3}_{-3.0}$ s. Note that this stretching can be the dominant contribution to $\Delta t_{\rm b}$ in case of source activity times of significantly less than one second as expected for the accretion timescale of post-merger disks.[2] The latter timescale is expected to vary with the torus mass. It is set by the viscous transport within the compact accretion torus, in contrast to collapsars where the accretion disk is fed by an external reservoir of several solar masses of stellar matter and the accretion timescale is therefore determined by the collapse timescale of the massive, rotating star. Even if the accretion phase of the remnant BHs of NS+NS or NS+BH mergers lasts only fractions of a second, our simulations suggest that such events can account for the measured durations of short GRBs. Of course, our estimation of $\Delta t_{\rm b}$ can only be considered as an exercise for demonstrating a fundamental possibility. It has to be taken with caution, because we need to extrapolate our hydrodynamic results over several orders of magnitude in radius. Extrapolation of our results from about 0.5 s (~ 0.4 s) after the onset (shutdown) of the energy release to more than 300 s later ignores how the fireball properties continue to change and how the long-time propagation and expansion of the fireball may depend on the structure of the ambient medium of the merger site. Moreover, the GRB emission might be shorter than our estimate if it is produced in a region that is smaller than the whole fireball. Nonthermal emission of radiation requires the dominant energy of the flow to be kinetic energy of relativistic baryons but not internal energy. Unfortunately our simulations had to be stopped before definite statements about the terminal fireball structure and the final ratio of its kinetic to internal energy were possible.

Our current work is a first step towards fully self-consistent models. So far we have investigated the relativistic hydrodynamic flow that is triggered by the deposition of energy near the BH-torus system. However, this energy release was prescribed according to a defined functional behavior instead of being linked to the neutrino emission of the evolving accretion torus. We are currently working in removing this limitation by preparing simulations of the viscosity-driven evolution of BH-torus systems with a simplified, but consistent treatment of neutrino transport and $\nu\bar{\nu}$-annihilation.

[2] However, this stretching effect might not change substantially the duration of a long-GRB (assuming that a similar phenomenon might happen during the propagation up to the transparency radius of a fireball yielding a long-GRB event).

Acknowledgments

MAA wish to thank the organizers for their support to attend Texas@Stanford conference. We thank M. Ruffert for providing us with data to construct our initial models. This work was partially supported by the Sonderforschungsbereich 375 "Astro-Teilchenphysik" and the Sonderforschungsbereich-Transregio 7 "Gravitationswellenastronomie" of the Deutsche Forschungsgemeinschaft. M.A.A. acknowledges the partial support of the Spanish Ministerio de Ciencia y Tecnología (AYA2001-3490-C02-C01) and the possibility of making use of the SGI-Altix computer of the University of Valencia.

References

[1] C. Kouveliotou, C. A. Meegan, G. J. Fishman, N. P. Bhat, M. S. Briggs, T. M. Koshut, W. S. Paciesas, and G. N. Pendleton, Astrophysical Journal **413**, L101 (1993).

[2] T. J. Galama, P. M. Vreeswijk, J. van Paradijs, C. Kouveliotou, T. Augusteijn, H. Bohnhardt, J. P. Brewer, V. Doublier, J.-F. Gonzalez, B. Leibundgut, C. Lidman, O. R. Hainaut, *et al.*, Nature **395**, 670 (1998).

[3] K. Z. Stanek, T. Matheson, P. M. Garnavich, P. Martini, P. Berlind, N. Caldwell, P. Challis, W. R. Brown, R. Schild, K. Krisciunas, M. L. Calkins, J. C. Lee, *et al.*, Astrophysical Journal **591**, L17 (2003).

[4] B. Pacyński, Astrophysical Journal **308**, L43 (1986).

[5] R. Mochkovitch, M. Hernanz, J. Isern, and X. Martin, Nature **361**, 236 (1993).

[6] R. Sari and T. Piran, Astrophysical Journal **485**, 270 (1997).

[7] M. Ruffert and H.-T. Janka, Astronomy and Astrophysics **344**, 573 (1999).

[8] M. A. Aloy, T.-H. Janka, and E. Müller, Astronomy and Astrophysics pp. Accepted 25/01/2005. astro–ph/0408291 (2005).
[9] M. A. Aloy, J. M. Ibáñez, J. M. Martí, and E. Müller, Astrophysical Journal Supplement Series **122**, 151 (1999).
[10] M. A. Aloy, E. Müller, J. M. Ibáñez, J. M. Martí, and A. MacFadyen, Astrophysical Journal Letters **531**, L119 (2000).
[11] H.-T. Janka, T. Eberl, M. Ruffert, and C. L. Fryer, Astrophysical Journal **527**, L39 (1999).
[12] M.-A. Aloy, J.-M. Ibáñez, J.-A. Miralles, and V. Urpin, Astronomy and Astrophysics **396**, 693 (2002).
[13] A. Levinson and D. Eichler, PRL **85**, 236 (2000).
[14] V. Kalogera, C. Kim, D. R. Lorimer, M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, *et al.*, Astrophysical Journal **601**, L179 (2004).
[15] C. L. Fryer, S. E. Woosley, and D. H. Hartmann, Astrophysical Journal **526**, 152 (1999).
[16] D. Guetta and T. Piran, ArXiv Astrophysics e-prints (2004), astro-ph/0407429.
[17] I. A. Morrison, T. W. Baumgarte, and S. L. Shapiro, Astrophysical Journal **610**, 941 (2004).
[18] S. Setiawan, M. Ruffert, and H.-T. Janka, MNRAS **352**, 753 (2004).
[19] L. Balázs, Z. Bagoly, I. Horváth, A. Mészáros, and P. Mészáros, AA **401**, 129 (2003).
[20] S. Mao, R. Narayan, and T. Piran, Astrophysical Journal **420**, 171 (1994).
[21] D. A. Frail, S. R. Kulkarni, S. R. Nicastro, M. Feroci, and G. B. Taylor, Nature **389**, 261 (1997).
[22] S. Rosswog and E. Ramirez-Ruiz, MNRAS **343**, L36 (2003).
[23] S. Rosswog and E. Ramirez-Ruiz, MNRAS **336**, 7 (2002).