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Producing short GRBs from coalescing compact binaries(*)

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Summary. — We present some of the results of a series of relativistic hydrodynamic simulations of compact binary mergers 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 in this kind of progenitor and the main characteristics of the resulting outflow.

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1. – Introduction

Due to their different duration and spectral properties, Gamma-Ray Bursts (GRBs) are commonly divided in two classes: short-hard (≤ 2 s) and long-soft (≥ 2 s) GRBs [7]. A number of broad-band (from radio to X-rays) afterglow observations have connected long GRBs to the same massive stars that are progenitors of Type I Supernovae (*e.g.,* [5,13]). A smaller number of short GRBs have been observed 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.,* [10,9]). 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 $\sim 10^{51}$ 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 [12], 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 [11].

In this work we summarize some of the findings of Aloy *et al.* [4] who address the question of whether a local deposition of energy above the accretion disk produced after the

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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.

2. – Initial model and numerical set-up

We use the high-resolution shock-capturing code GENESIS [1, 2] 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 $3\,M_\odot$ (type-A models) and $2.44\,M_\odot$ (type-B models) 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.* [4]. 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 $R_{\rm max} = 2 \cdot 10^{10}$ 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 $30° - 75°$. From the annihilation rate distribution computed in [11] and [6], 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

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 (during an interval of the order of the free falling time of the fluid located at distances comparable with the torus radius) 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 ($\lesssim 8°$), or relatively wide opening angle ($\lesssim 25°$) winds

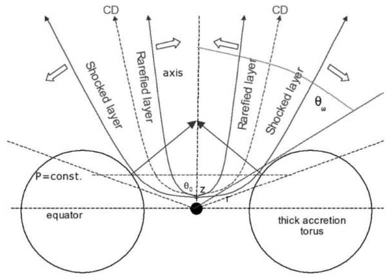

Fig. 1. – Scheme of the collimation process of the fireball produced after the merger of a compact binary system. The limits of the deposition region are marked by dashed lines. The empty arrows show the direction of propagation of each of the discontinuities that develop from the interface (*i.e.,* 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.

(*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 or, independently of the deposition rate, diluted environments, tend to form conical, ultrarelativistic ($\Gamma \gtrsim 400$) winds. In the case of type-A models, these winds are smooth, their radial leading edges propagate at relativistic speeds ($\sim 0.97c$) and can be fitted by analytic power laws. In the case of type-B models, the radial leading edges propagate at ultrarelativistic velocities ($\gtrsim 0.9999c$; because there is much less mass in the ambient) and the outflows are rather irregular due to the effect of large Kelvin-Helmholtz (KH) or shear driven [3] instabilities originating from their interaction either with the torus, or with the environment. 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 (and simultaneously speeded 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 [4] 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 and Eichler [8].

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 ($\dot{E} < 10^{51}\mathrm{erg\,s^{-1}}$) to ultrarelativistic wind-like outflows ($\dot{E} > 10^{51}\mathrm{erg\,s^{-1}}$). In models of type-B, we find ultrarelativistic winds for all energy deposition rates considered ($\dot{E} > 5 \cdot 10^{48}\mathrm{erg\,s^{-1}}$). 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 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 $\gtrsim 75^\circ$ (model B03 in [4]), 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). 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. This points to the possibility that the duration of the GRB emission can be much larger than the time of the activity (*i.e.,* of release of energy) of the central source.

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