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RELATIVISTIC OUTFLOWS IN GAMMA-RAY BURSTS

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RESUMEN

La posibilidad de que las erupciones de rayos gamma (GRBs) no sean emisiones isotrópicas fue considerada teóricamente para atenuar el problema asociado a la gran cantidad de energía implicada por el modelo de bola de fuego estándar para estos potentes fenómenos. Sin embargo, el mecanismo por el cual, tras la deposión cuasi-isotrópica de unos pocos 10^{50} erg se origina una eyección colimada de plasma no pudo ser explicada de forma satisfactoria analíticamente. La razón de ello radica en que la colimación de un flujo saliente por su sistema progenitor depende de una dinámica no lineal muy compleja. Ello ha hecho necesario el uso de simulaciones numéricas para arrojar algo de luz sobre la viabilidad de algunos de los progenitores más probables de GRBs. En esta contribución revisaré los hechos más relevantes mostrados por tales simulaciones numéricas y cómo éstas han sido utilizadas para validar el modelos de estrella colapsante (para GRBs largos) y el modelo que implica la fusión de un sistema binario de objetos compactos (para GRBs cortos).

ABSTRACT

The possibility that gamma-ray bursts (GRBs) were not isotropic emissions was devised theoretically as a way to ameliorate the huge energetic budget implied by the standard fireball model for these powerful phenomena. However, the mechanism by which after the quasy-isotropic release of a few 10^{50} erg yields a collimated ejection of plasma could not be satisfactory explained analytically. The reason being that the collimation of an outflow by its progenitor system depends on a very complex and non-linear dynamics. That has made necessary the use of numerical simulations in order to shed some light on the viability of some likely progenitors of GRBs. In this contribution I will review the most relevant features shown by these numerical simulations and how they have been used to validate the collapsar model (for long GRBs) and the model involving the merger of compact binaries (for short GRBs).

Key Words: **GAMMA-RAYS: BURSTS — ISM: JETS AND OUTFLOWS — MHD**

1. INTRODUCTION

Our current understanding is that gamma-ray bursts (GRBs) are produced in the course of the birth of a stellar-mass black hole (BH). In other astrophysical systems where accreting BHs fuel collimated beams of plasma (e.g., AGNs and BH–X-ray binaries), there is a direct evidence for relativistic outflows and jet collimation which comes from the imaging of the system. Therefore, it seems reasonable to assume as starting point, that also GRBs result from relativistic, collimated outflows from accreting, stellar-mass BHs. We have inferred that outflows yielding GRBs are relativistic because of a couple of observational constraints, namely, the detection of radio scintillation of the interstellar medium (Frail et al. 1997) and the measurement of superluminal proper motions in imaged afterglows (Taylor et al. 2004). The ultrarelativistic expansion is also necessary to overcome the theoretical constrain imposed by the compactness problem (Cavallo & Rees 1978). However, we only have an indirect evidence of collimation based on the observational constraint posed by the achromatic break in the afterglow light curve of some GRBs (e.g., Harrison et al. 1999). From the theoretical point of view, if GRBs are collimated events, the true emitted energy E_γ is reduced by a factor $f_\Omega \simeq \theta^2/2$ (Rhoads 1999; Sari et al. 1999), i.e., $E_\gamma = f_\Omega E_{\gamma,\mathrm{iso}}$, where $E_{\gamma,\mathrm{iso}}$ is the detected equivalent isotropic energy. Nonetheless, the mechanism by which after the quasi-isotropic release of an amount of energy in the range $10^{48} - 10^{51}$ erg results in a collimated ejection has not satisfactory been explained analytically. The reason being that the collimation of an outflow by the progenitor system depends on a very complex and non-linear dynamics. That has made necessary the use of numerical simulations in order to understand the collimation mechanism as well as to shed some light on the viability of some systems proposed to be the progenitors of GRBs. A robust result obtained in numerical simulations of

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generation of GRBs is that the progenitor system yields collimated outflows under rather general conditions independent on whether the outflow is initiated thermally (e.g., Aloy et al. 2000, 2005) or it is magnetically driven (McKinney 2006).

In this contribution I will review the most relevant features shown by these numerical simulations and how they have been used to validate the collapsar model (for long GRBs; § 2) and the model involving the merger of compact binaries (for short GRBs; § 3).

2. OUTFLOWS EMERGING FROM PROGENITORS OF LONG GRBS

Among the plethora of models devised to explain the origin of long GRBs (lGRBs), the most widely accepted was put forward by Woosley. In the original *collapsar* model, also known as *failed supernova* model (Woosley 1993), the collapse of a massive ($M_{\rm ZAMS} \sim 30 M_\odot$) rotating star that does not form a successful supernova but collapses to a BH ($M_{\rm BH} \sim 3 M_\odot$) surrounded by a thick disk. The viscous accretion of the disk matter onto the BH yields a strong heating that, in its turn, produces a copious amount of thermal neutrinos and antineutrinos, which annihilate preferentially around the rotation axis producing a fireball of e^+e^- pairs and high energy photons. Later it was noted that, perhaps ν–powered fireballs might not be sufficiently energetic to fuel the most powerful GRB events and, thus, the collapsar model was extended to account for alternative energy extraction mechanisms (MacFadyen et al. 2001). More explicitely, the accretion energy of the torus could be tap by sufficiently strong magnetic fields (*hydromagnetic* generation) by means of the Blandford-Payne process (Blandford & Payne 1982), or a non-trivial fraction of the rotational energy of the BH may also be converted into a Poynting flux (Blandford & Znajek 1977).

The scape of the newly born fireball and its terminal Lorentz factor (Γ_∞) depend on structural and on dynamical factors. The critical structural factors are the environmental baryon density in the funnel around the rotation axis of the star and the ability of the progenitor star to loose its outer Hydrogen envelope. An under-dense funnel forms along with the accretion torus if the specific angular momentum of the core of the star lies in the range $3\times 10^{16}\,{\rm cm^2\,s^{-1}} \lesssim j \lesssim 2\times 10^{17}\,{\rm cm^2\,s^{-1}}$ (MacFadyen & Woosley 1999). The existence of the funnel is key to collimate the fireball and to permit its propagation through the progenitor. The most favourable conditions for the generation and propagation of the fireball happen when the density of the funnel ($\rho_{\rm f}$) is much smaller than the density of the torus ($\rho_{\rm torus}$), namely, $\rho_{\rm f}/\rho_{\rm torus} \lesssim 10^{-4} - 10^{-3}$ (MacFadyen & Woosley 1999). The likelihood that the progenitor star had lost its Hydrogen envelope depends on a number of factors which occurrence is still a matter of debate like, e.g., the generation of stellar winds, the interaction with a companion (Podsiadlowski et al. 2004), etc. The relevance of the lost of the hydrogen envelope resides on the fact that, unless the density of the funnel is extremely small (as proposed by Mészáros & Rees 2001), only a mildly relativistic, poorly-collimated fireball would reach the outer edge of the hydrogen envelop after very long times and with relatively small Lorentz factors ($\Gamma \simeq 2$) implying that the observational signature would be an X–ray/UV transient with a duration of $\sim 100 - 1000$ s but not a GRB (MacFadyen et al. 2001). Finally, the most important dynamical factor setting Γ_∞ is the the amount of baryons entrained as the fireball propagates through the stellar mantle.

Several analytic works have made estimates about the collimation angle and the Lorentz factor when the fireball breaks out the surface of the star (e.g., Mészáros & Rees 2001). Nevertheless, the complexity inherent to the non-linear (magneto)hydrodynamic interaction of the fireball plasma with the stellar environment makes it unavoidable the use of numerical simulations. With these simulations we have been able to give preliminary answers to the following questions:

Collimation. The generated outflows are inertially or magnetically confined. In the first case, the collimator is the funnel within the progenitor while in the second case, the flow is self-collimated by its own magnetic field if it is strong enough. Rather independently on the initial conditions and on the inclusion of magnetic fields, the typical outflow half-opening angles, when the jet reaches the surface of the progenitor star, are $\theta_{\rm break} \lesssim 5°$. These small half-opening angles result from the recollimation of the outflow within the progenitor and they are independent on whether the boundary conditions are set to initiate the jet with much larger half-opening angles (e.g., $\theta_0 = 20°$; Zhang et al. 2003) or on whether the jet is generated by an energy release into a volume spanning a half-opening angle $\theta_{\rm d} = 30°$ much larger than $\theta_{\rm break}$ (Aloy et al. 2000). In the course of their propagation through the progenitor the jets develop a non-homogeneous structure, transverse to the direction of motion, whose main features are an internal ultrarelativistic spine (where the Lorentz factor may reach $\Gamma_{\rm core} \sim 30 - 50$ at jet breakout) within a half-opening angle of $< 2°$ laterally endowed by a moderately relativistic, hot shear layer ($\Gamma_{\rm shl} \sim 5 - 10$) extending up to $\theta_{\rm shl} < 20° - 30°$ (Aloy et al. 2002). We point out that the transverse structure of the jet is *nearly* Gaussian both in simulations including magnetic fields (e.g., McKinney 2006) or not including them (e.g., Aloy et al. 2000). However, a more accurate fit of the transverse structure of the jet, cannot be accommodated by a simple Gauss function (Aloy 2001).

Variability. All produced outflows are highly variable due to the generation of Kelvin-Helmholtz (Aloy et al. 2000; Gómez & Hardee 2004), shear-driven (Aloy et al. 2002) or pinch magnetohydrodynamic (MHD) instabilities (McKinney 2006). Such *extrinsic* variability is independent on the (*intrinsic*) variability of the energy source and leads to the formation of irregularities in the flow which are the seeds of internal shocks in the outflow. Except in cases in which the source may produce quasi-periodic variability (perhaps induced by precession or nutation modes of the accretion disc), the extrinsic variability might be indistinguishable form the intrinsic one. Numerical simulations of three-dimensional (3D) relativistic jets propagating through collapsar-like environments show that such jets are also stable (Zhang et al. 2004) but it still remains unknown whether 3D relativistic, magnetohydrodynamic, collapsar-jets will also be stable along its whole trajectory.

Jet breakout. The jets generated are much lighter than their baryon reach environments. Thus, they propagate through the collapsar at moderate speeds ($\sim 0.3c$) and fill up thick cigar-shaped cavities or cocoons of shocked matter that also propagates along with the beam of the jet and that, eventually may break the surface of the collapsar. Since in the cocoon a few 10^{50} erg may be stored as the jet drills its way through the star, it has been proposed that its eruption through the collapsar surface could yield a number of γ-ray/X-ray/UV-transients (Ramirez-Ruiz et al. 2002). Indeed, it has been proposed that GRBs are but one observable phenomenon accompanying black hole birth and other possibilities may arise depending on the observer's viewing angle with respect to the propagation of the ultrarelativistic jet (Woosley 2000). Thus, in a sort of unification theory for high-energy transients, one may see progressively softer events ranging from GRBs (when the jet emergence is seen almost head on) to UV flashes (when the jet eruption is seen at relatively large polar angles) and accounting for X-ray rich GRBs (XRR-GRBs) and X-ray flashes (XRF) at intermediate angles. The jet emergence through the stellar surface and its interaction with the stellar wind (which likely happens during the late stages of the evolution of massive stars) could lead to some precursor activity (MacFadyen et al. 2001). Furthermore, ν–powered jets are very hot at breakout ($\sim 80\%$ of the total energy is stored in the form of thermal energy) which implies that jets can still experience an additional acceleration by conversion of thermal into kinetic energy, even if the energy source has ceased its activity.

2.1. *lGRBs produced in collapsars: MHD- or neutrino-powered jets?*

From a aesthetic point of view, it is beautiful if any invoked jet powering mechanism explains not only events with relatively *small* Lorentz factors $\Gamma \sim 100$ but also the occurrence of events with very large inferred values of $\Gamma \sim 500$ (Lithwick & Sari 2001) or even $\Gamma \sim 1000$ as suggested by models for some GRBs (Soderberg & Ramirez-Ruiz 2003). However, there are no fundamental reasons to argue in favour of a unique and universal mechanism to extract the energy stored in the progenitor.

Purely hydrodynamic, ν-powered jets in collapsars of type-I seem to be able only to produce more moderate terminal values of the bulk Lorentz factor ($\Gamma \sim 100 - 400$; e.g., Aloy et al. 2000; Zhang et al. 2003), even if there is a further acceleration of the forward shock as a result of an appropriate density gradient in the medium surrounding the progenitor (Aloy et al. 2000), unless the density in the funnel around the rotation axis is very small (Mészáros & Rees 2001). In collapsars of type-II the mass accretion rate ($\dot{M} \sim 10^{-3} - 10^{-2} M_\odot\,{\rm s}^{-1}$) is insufficient to produce a ν-powered jet, but it may suffice to generate MHD-powered jets whose observational signature might be weak, poorly collimated X-ray/UV transients or very long ($\sim 100 - 1000$ s) GRBs of low $E_{\rm iso}$ and small Γ if the progenitor star is able to loose its Hydrogen envelope (MacFadyen et al. 2001).

From extrapolations of the numerical results of axisymmetric jets generated electromagnetically (McKinney 2006) very large values of the asymptotic Lorentz factor of the outflow ($\Gamma_\infty \sim 1000$) can be attained. Thus, it seems rather plausible that MHD mechanisms have to be employed to generate jets with $\Gamma \sim 500-1000$ (McKinney 2005, 2006) and, invoking the existence of a universal energy extraction mechanism, one may also argue that also jets with much more moderate terminal Lorentz factors are also MHD-generated. Nevertheless, these arguments have a number of issues:

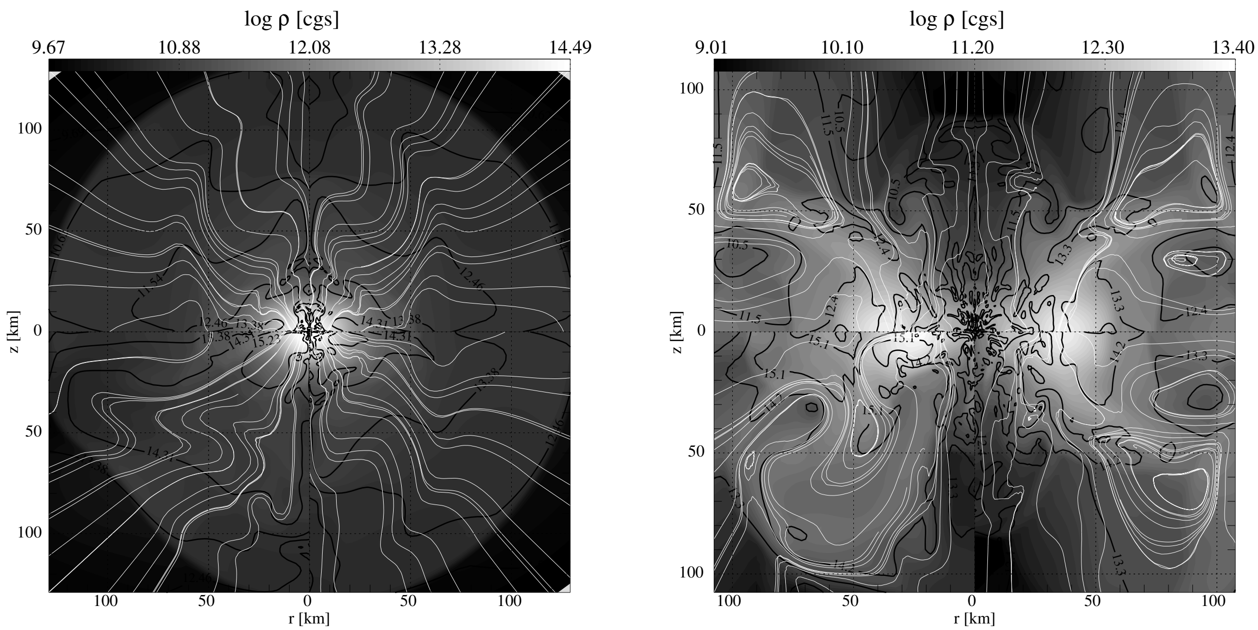

Fig. 1. Logarithm of the density (gray-scale) with overimposed magnetic field lines (white lines) and total magnetic field strength (black contours) corresponding to models collapsing stellar cores with a small initial rotational energy and rotating almost rigidly (left) and with a larger initial rotational energy and differentially rotating (right). Each panel displays the state of the stellar core after the bounce for four different initial magnetic field strengths ($B_0 = 10^{10}\,$G, $10^{11}\,$G, $10^{12}\,$G and $10^{13}\,$G in the clockwise direction starting from the upper left corner). The figures correspond to models of Obergaulinger et al. (2006a).

1.- The estimates of the terminal Lorentz factor of MHD-generated jets are based on axisymmetric models. The 3D-stability of relativistic magnetized jets is still a matter of debate which needs of much more complex numerical simulations than the ones produced so far. Should 3D-MHD jets be unstable, should the terminal Lorentz factor not reliably be calculated with the state-of-the-art axisymmetric, general relativistic, MHD (GRMHD) simulations up to date (McKinney 2006).

2.- GRMHD initial models of accreting BH systems consist on more or less realistic matter distributions over which an assumed poloidal field is imposed, i.e., they are not the result of a consistent magneto-rotational core collapse (e.g., Mizuno et al. 2004a,b; McKinney 2006). The use of poloidal fields is triggered by the fact that purely toroidal field configurations do not yield the production of bipolar jets (De Villiers et al. 2005). On the other hand, the initial magnetic field strengths are assumed, not consistently computed from the core collapse of massive stars. Typically, initial field strengths as large as $B \sim 10^{15} - 10^{16}\,$G are used. Such large values of B in combination with maximal values of the dimensionless angular momentum of the BH ($j_{\rm BH} \sim 1$) are necessary in order to efficiently extract energy via Blandford-Znajek (BZ) mechanism, because the BZ-power scales rather sensitive with B as $\dot{E}_{\rm BZ} \sim 10^{50} j_{\rm BH}^2 (M_{\rm BH}/3M_\odot)^2 (B/10^{15}\,{\rm G})^2\,{\rm erg\,s^{-1}}$, (Lee et al. 2000).

3.- When numerical simulations of the magnetorotational core collapse of massive stars are performed (see, e.g., Obergaulinger et al. 2006a,b, and references therein), bipolar outflows as well as thick toroidal structures surrounding a central, low density funnel in the collapsed core are only generated for initial magnetic field strengths $B_0 \gtrsim 10^{12}\,$G and for rather fast[3] and differentially rotating stellar cores (Figure 1 right). Such initial field strengths and angular velocities are well beyond the ones predicted by the state-of-the-art calculations of rotating massive stars (Heger et al. 2005). These initially strongly magnetized models likely develop collapsed cores, with a mass of $M_{\rm c} \sim 1 M_\odot$ and a specific angular momentum $J_{\rm c} \sim 10^{16}\,{\rm cm^2\,s^{-1}}$, and may form a rapidly rotating BH with $j_{\rm BH} \sim 1$. Furthermore, the winding up of the initial poloidal field leads to maximal field strengths $B_{\rm max} \sim 10^{15}\,$G, being the field pre-

[3]The rotational energy being as large as $\sim 4\%$ of the gravitational energy.

dominantly toroidal $B_{\rm toroidal}/B_{\rm poloidal} \sim 1 - 10$. On the other hand, initially rigid, more moderately rotating cores do not yield tori around low-density funnels, do not produce bipolar jets and the maximum field strengths are $\sim 5 \times 10^{14}$ G (Figure 1 left). Considering that the collapsed cores are smaller ($M_{\rm c} \sim 0.75 M_{\odot}$) and slowly rotating ($J_{\rm c} \sim 2 \times 10^{15}\,{\rm cm}^2\,{\rm s}^{-1}$) than in the previous case one may expect that the newly born BH resulting from the posterior evolution of these kind of cores will not be a maximally rotating but, instead, they will form BHs with more moderate $j_{\rm BH} \sim 0.6$. Thereby, the conclusion that seems to emerge from detailed numerical simulations of Obergaulinger et al. is that if the initial magnetic field strength and rotational energy is as small as predicted by the most detailed stellar evolution models, the collapsed core does not hold the appropriate conditions ($B \gtrsim 10^{15}$ G, $j_{\rm BH} \sim 1$) to efficiently extract energy via BZ-mechanism and, conversely, *unrealistically* large initial magnetic fields and rotational energies need to be invoked to expect a BZ-like mechanism to operate efficiently. However, we have to be cautious in order not to extract too far reaching conclusions from the previously mentioned numerical work. It remains true that the results of the simulations of Obergaulinger et al. are handicapped because they do not include general relativity, because the numerical resolution is still small to capture all the relevant magneto-rotationally unstable modes and, because they are restricted to axisymmetric models.

From the above points, one may infer that the dynamical relevance of the magnetic field in the process of energy extraction from the central source will depend on fine details of the magnetorotational collapse of the collapsar core. On the other hand, the process of $\nu\bar{\nu}$-annihilation as the primary source of energy that fuels an ultrarelativistic fireball also needs of a more careful study in order to know how much energy such a process may release in the progenitor system and how such an amount of energy depends on the physical conditions of the progenitor.

A step towards such goal is the work of Birkl et al. (2006), which contributes to better understand how the energy deposition rate due to the process of $\nu\bar{\nu}$-annihilation ($\dot{E}_{\nu\bar{\nu}}$) depends on general relativistic (GR) effects and on different neutrinosphere geometries in hyperaccreting stellar-mass BH systems. Birkl et al. consider two families of neutrinospheres. On the one side, idealized geometries as thin disks, tori, and spheres. On the other side, more realistic models are constructed as non-selfgravitating equilibrium matter distributions for varied BH rotation. Independent of whether GR effects are included, considering the same values of temperature and surface area for an isothermal neutrinosphere, thin disk models yield the highest energy deposition rates by $\nu\bar{\nu}$-annihilation, while spherical neutrinospheres lead to the lowest ones. Considering isothermal neutrinospheres with the same temperature and surface area, it turns out that compared to Newtonian calculations, GR effects increase the annihilation rate measured by an observer at infinity by a factor of 2 when the neutrinosphere is a disk (in agreement with the previous works; Asano & Fukuyama 2001). However, in case of a torus and a sphere the influence of GR effects is globally only $\sim 25\%$, although locally, particularly in the vicinity of the rotation axis of the system, it can be significantly larger. Focusing on the dependence of the energy deposition rate on the value of $j_{\rm BH}$, it is found that increasing it from 0 to 1 enhances the energy deposition rate measured by an observer at infinity by roughly a factor of 2 due to the change of the inner radius of the neutrinosphere. Furthermore, although the absolute values of the energy deposition rate have to be taken with care (because of the steady state approximation used and the need of more realistic models for the accretion disk; see Birkl et al. 2006, for accretion disks of mass similar to the one expected in the collapsar model ($M_{\rm disk} \lesssim 0.01 M_{\odot}$) typically, $\dot{E}_{\nu\bar{\nu}} \sim 10^{50} - 10^{51}{\rm erg\,s}^{-1}$. Even if only an small fraction ($\sim 10\%$) of that energy were used to boost a polar outflow, there is fair chance for neutrinos to be the dominant energy source of the fireball (at least, in some cases when the magnetic field is not too large). The most likely scenario that can be devised is that both mechanisms (MHD and neutrino energy release) might be operating simultaneously. Indeed, for MHD-produced jets, neutrinos will play a fundamental role in the pair-loading of the jet (e.g., Levinson & Eichler 1993) while, for ν-powered jets, the magnetic field may be important to collimate the thermally generated outflow. Which of the two energy deposition mechanisms dominates in every single GRB will depend on the exact conditions in the precollapse progenitor.

3. OUTFLOWS EMERGING FROM PROGENITORS OF SHORT GRBS

Nowadays, it is commonly believed that short GRBs (sGRBs) are generated after the merger of a system compact binaries formed by either two neutron stars (NSs) or a neutron star and a BH (Paczynski 1986; Goodman 1986; Eichler et al. 1989; Mochkovitch et al. 1993). The remnant left by the merger consists of a newly born BH black hole girded by a thick gas torus from which it swallows matter at a hypercritical rate. In such situation radiation is advected inward with the accretion flow and the cooling is dominated by the emission of neutrinos (Popham et al. 1999). As in the case of progenitors of lGRBs, these neutrinos might either be the primary energy source blowing a fireball of e^+e^- pairs and photons or to act as mediator in hydromagnetic or electromagnetic energy extraction mechanisms (see § 2) to pair-load the Poynting dominated outflow. A fundamental difference with respect to the collapsar model is that the accretion thick disk is cannot be continuously refilled from a surrounding matter reservoir (the stellar matter in case of a collapsar) and, therefore, the duration of the produced outflows is, in part (see Aloy et al. 2005) roughly limited by the time during needed by the black hole to engulf most of the matter of the accretion disk, namely, a few 100 ms. This limit on the time scale, set by the ON time $t_{\rm ce}$ of the source, of holds for both ν-powered jets and for MHD-generated outflows. In the first case, the neutrino luminosity fades as the mass of the disk decreases and, thereby, there will be a critical torus mass below which a plasma outflow cannot be sustained. In the second case, for the same reason, there will not be sufficient neutrinos that pair-load the Poynting dominated jet after a sizable fraction of the torus has been accreted.

Although it seems likely that releasing a few 10^{49} erg above the poles of a stellar mass BH in a region of nearly vacuum may yield an ultrarelativistic outflow, numerical simulations are needed to attempt to answer questions about the collimation mechanism of the polar outflow, the opening angle of the ultrarelativistic ejecta, the asymptotic Lorentz factors that can be attained, the internal structure of the outflow, the duration of a possible GRB event, and the isotropic equivalent energy which an observer would infer by assuming the source to expand isotropically. These questions may at most be guessed, but they cannot be reliably answered on grounds of merger models and a consideration of their energy release by neutrino emission and the subsequent conversion of some of this energy by $\nu\bar{\nu}$-annihilation to e^+e^- pairs (Ruffert & Janka 1999; Janka et al. 1999; Rosswog & Ramirez-Ruiz 2002; Rosswog et al. 2003; Birkl et al. 2006). Only self-consistently time-dependent (magneto)hydrodynamic modeling may give us some insight on the former questions. The reason being that the relativistic outflow develops in a complex interaction with the accretion torus, cleaning its own axial funnel such that later energy deposition encounters a much reduced baryon pollution.

Some keys to answer the questions mentioned in the previous paragraph have been very recently revealed by time-dependent numerical simulations in which the main results are:

Collimation. The generated outflows which may yield GRB signatures are either collimated by the accretion disk (Aloy et al. 2005) or self-collimated by the magnetic field (McKinney 2006), depending on whether the jet is initiated thermally or magnetically, respectively. The typical outflow half-opening angles are $\sim 3° - 25°$ and, as in the case of jets produced in collapsars, the baryon-poor outflows display a transverse structure. This structure shows a central core which spans a half opening angle $\theta_{\rm core} < 3° - 12°$ where $\Gamma_{\rm core} > 100$ flanked laterally by a layer, extending up to $\theta_{\rm shl} \sim 25°$ where the Lorentz factor smoothly decays to moderately relativistic values and where a sizable fraction of the total energy is stored. This layer is rather hot in thermally initiated outflows and has the potential of accelerating even after the energy release by the central engine has ceased. Similar to the jets produced in collapsar environments the transverse structure of the Lorentz factor could be roughly fit by Gaussian profiles. However, somewhat more complicated functions are required to provide more accurate fits (Aloy et al. 2005).

Variability. Even injecting energy close to the BH even horizon at constant rates, the produced outflows are highly variable. The interaction of the newborn fireball with the accretion torus yields the growth of Kelvin-Helmholtz (Aloy et al. 2005) instabilities. The variability in case of MHD jets is imprinted by pinch instabilities (McKinney 2006). Up to date only axisymmetric models have been computed. All of which seem to be stable or marginally stable. It is not yet numerically verified whether 3D jets emerging from hyperaccreting BHs are stable.

Influence of the environment. Mergers of compact objects may take usually place in the intergalactic medium or in the outer skirts of their host galaxies. Thus, the environment of the merger may have a very low density. However, in the course of the merger, after the first contact of the two compact objects, there is an ejection of matter, which is larger close to the orbital plane. Such matter forms a cool baryon reach environment with a mass $M_{\rm halo} <$ a few $10^{-2} M_\odot$ (Ruffert & Janka 2001; Oechslin & Janka 2006). The exact amount of mass ejected sensitively depends on whether the two compact objects are both NSs or one of them is a BH, on the initial mass ratio between the two, etc. Thereby, when the central BH forms, the newly born system may, in some cases, be embedded into a relatively high density halo. Mergers in low density environments may fuel ultrarelativistic outflows with the potential to produce *normal* sGRBs, while in case that the merger occurs in high density media, the observational signature is not a sGRB but, most likely, a flash in the soft X-ray or UV bands (Aloy et al. 2005). In the latter case, the resulting event might only be observable if it happens very close to the Milky Way. The fact that depending on the environmental density an sGRB can be produced or not has the direct implication that not every merger may yield a sGRB. This fact has to be considered when making estimates about the true rates of sGRBs and compared with the rates of NS+NS mergers (e.g., Guetta & Piran 2005).

Asymptotic Lorentz factor. The saturation value of the outflow Lorentz factor, Γ_∞, is difficult to estimate on the basis of numerical simulations that cover only the initial fraction of a second in the evolution of an ultrarelativistic outflow generated in a hyperaccreting BH. Despite this difficulties rough estimates can be made. For instance, in case that the outflows are thermally generated (Aloy et al. 2005), there is a clear trend to produce much higher values of Γ_∞ for sGRBs ($\Gamma_\infty \gtrsim 500 - 1000$) than for lGRBs ($\Gamma_\infty \sim 100$). The reason for the difference resides on the much smaller density of the environment of the merger (even accounting for the mass ejected from the compact objects after the first contact; see above) as compared with the baryon-polluted environment that a relativistic jet finds inside a collapsing massive star. It has been speculated that this difference in Lorentz factor might be the reason for the paucity of *soft* sGRBs (Janka et al. 2006). The former trend seems not to be followed by MHD-generated outflows (McKinney 2006). The most likely reason being that McKinney's simulations are set to be scale free, while there should be a big difference between the environments of mergers of compact objects and the interior of collapsars. Probably, such a difference cannot be accommodated easily with simple scale-free power-laws for the distribution of the physical variables.

Duration of the events. As pointed out by Aloy et al. (2005) and Janka et al. (2006), the "shells" ejected by the central engine, accelerate much faster in the leading part of the outflow than the shells in its lagging part. The rear shells therefore need a longer time to reach velocities $v \simeq c$. This differential acceleration at early and late times of the relativistic jet leads to a stretching of the overall radial length of the outflow, Δ, relative to $t_{\rm ce}$ times the speed of light c, $\Delta > ct_{\rm ce}$. This stretching has the important consequence that the overall observable duration of the GRB (in the source frame), $T = t_\Delta = \Delta/c$, may be a factor of 10 or more longer than $t_{\rm ce}$, even when the GRB is produced by internal shocks.

4. SUMMARY

The numerical modelling of progenitors of GRBs has allowed us to gain some insight into a number of important issues related with the nature of the outflows produced by these systems. First, it has allowed us to verify that some (but probably not all) collapsars can yield collimated relativistic outflows that turn into lGRBs at large distances from the source. Likewise, only a fraction of the mergers of compact objects may yield sGRBs. Second, the numerical modeling has given us information about the collimation mechanism and typical outflow opening angles. Third, it has shown that the outflow is heterogeneous both along the direction of propagation and transverse to it, even if the central engine releases energy at a constant rate. Fourth, it seems rather plausible that some lGRBs with very high Lorentz factor ($\Gamma >> 100$) need of a MHD jet-formation mechanism. On the other hand, some other lGRBs with more moderate Lorentz factors ($\Gamma \sim 100$) can be explained by ν-powered jets, particularly if $t_{\rm ce} < 10\,$s. Fifth, MHD- and ν-mechanisms may work simultaneously. Therefore, it is likely that, in some cases MHD processes dominate the jet generation while in others neutrinos may be the dominant energy source.

The numerical modeling done so far is still insufficient. In order to start from consistent initial models, the state-of-the-art numerical codes must incorporate, at least, the effects of strong gravity, magnetic fields and a detailed neutrino transport. In the near future we may see how all these elements are included in more realistic numerical experiments that will deepen our understanding on how ultrarelativistic outflows are produced in progenitors of GRBs.

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