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From neutron star binaries to gamma-ray bursts(*)

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Summary. — I summarize recent results about how a neutron star binary coalescence can produce short gamma-ray bursts (GRBs). Two possibilities are discussed: the $\nu_i\bar{\nu}_i$-annihilation above the merged remnant and the exponential amplification of magnetic fields in the central object up to values close to equipartition. We find that the annihilation of $\nu_i\bar{\nu}_i$-pairs drives bipolar, relativistic outflows with Lorentz-factors large enough to circumvent the GRB "compactness problem". The total energy within these outflows is moderate by GRB-standards ($\sim 10^{48}$–10^{49} ergs), but the interaction with the baryonic material blown-off by the neutrinos collimates the outflows into opening angles of typically 0.1 sterad, yielding isotropic energies close to 10^{51} ergs. We further want to stress the plausibility of the central object resisting the immediate collapse to a black hole. In this case the central object will —similar to a proto-neutron star— be subject to neutrino driven convection that —together with the rapid, differential rotation— will lead to a drastic amplification of pre-existing magnetic fields. Within fractions of a second, field strengths comparable to equipartition field strength ($> 10^{17}$ G) will be reached. These will produce large torques that will spin-down the object within about 0.2 s, and would thus naturally explain the duration of short GRBs.

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1. – Introduction

Since nearly two decades coalescences of double neutron star systems (DNSs) are thought to cause gamma-ray bursts (GRBs). This possibility has been mentioned by Paczyński (1986), Goodman (1986), Goodman *et al.* (1987) and discussed in detail by Eichler *et al.* (1989) and Narayan *et al.* (1992) (for a more detailed bibliography see the reviews of Mészáros (2002) and Piran (2005)).

The coalescence of two neutron stars releases a gravitational binding energy of a few times 10^{53} ergs and therefore more than enough to power a short GRB with a gamma-ray energy of $E_\gamma \sim 10^{51}\left(\frac{\Omega}{4\pi}\right)$ ergs, Ω being the solid angle into which the photons are emitted. Due to its compactness such a merger can produce substantial variations in

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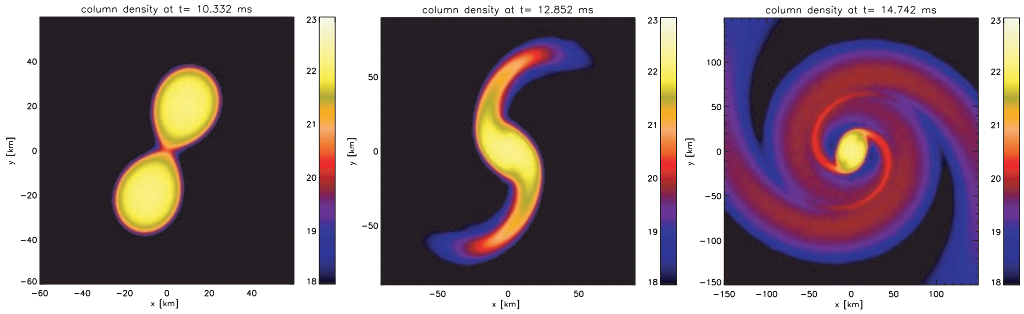
its energy output on very short time scales: a neutron-star like object has a dynamical time scale $\tau_{\mathrm{dyn,ns}} = (G\bar{\rho})^{-1/2} = 0.4\ (\bar{\rho}_{14})^{-1/2}$ ms, the orbital time scale at the marginally bound orbit of a new-born black hole is $\tau_{\mathrm{dyn,bh}} \approx \frac{16\pi G M_{\mathrm{BH}}}{c^3} = 0.2 \left(\frac{M_{\mathrm{BH}}}{2.5 M_\odot}\right)$ ms.

For several years there has been a discrepancy of about one order of magnitude between rates estimated based on the number of observed systems and those derived from population synthesis models. The recent discoveries of several new DNS (Stairs 2004, Faulkner 2005) have substantially increased the observation-based estimates, now being in good agreement with the population synthesis-estimate of about $\sim 10^{-4}$ events per year and galaxy (Kalogera *et al.* 2004). The rate of GRBs is estimated to be $\sim 10^{-7}$ per year and galaxy with about 25 % of which belong to the short variety of bursts (Hurley *et al.* 2002). Therefore, even if most DNS mergers should fail to produce detectable GRBs (either due to very narrow beaming or failure to produce a GRB at all), the neutron star merger rate would still be high enough to explain all short GRBs.

Most often it is assumed that the remnant of a DNS coalescence will immediately form a black hole that is surrounded by an accretion disk of neutron star debris. Therefore the coalescence of a neutron star black hole system, to our knowledge first suggested by Paczyński (1991), is generally only considered to be a variation on the DNS merger theme. Although this is a reasonable assumption, we want to point out two problems with this scenario. First, there is a controversy about the rate of such events. Bethe and Brown (1998) estimated rates as high as 10^{-4} per year and galaxy while a recent study (Pfahl *et al.* 2005) estimates that there is less than one black hole pulsar system per 100 DNS systems. This fraction would be consistent with the non-observation of black-hole neutron star systems while there are to date 8 DNS systems known. Second, even if their number should in principle be sufficient, the accretion process is considerably more complex than in the DNS case as there is a much larger range of possible mass ratios, leading to mass transfer whose dynamics is governed by the interplay between gravitational wave emission backreaction (trying to decrease the orbital separation), mass transfer (trying to widen the orbit) and the reaction of the neutron star to mass loss (depending on the nuclear equation of state and on the current neutron star mass). Using conventional nuclear physics, *i.e.* neutrons and protons as the only hadronic constituents of neutron star matter, we found it difficult (Rosswog *et al.* 2004, Rosswog 2005) to produce accretion disks that are likely to launch a GRB. This issue will have to be explored further in the future.

2. – Pathways to a GRB

We will now address possible pathways that lead from the coalescence, see fig. 1, to the production of the ultra-relativistic outflow that is required to accommodate the large energies and the variations on millisecond time scales with non-thermal spectra. To be consistent with observations, the GRBs are required to have Lorentz-factors Γ of several hundreds (Litwick and Sari 2001). Such Lorentz-factors can only be obtained if the available energy, E, is deposited in a volume that contains only a small amount of baryonic material, $m \sim E/\Gamma c^2$. Possible mediators to transport the energy into a baryon-poor region are the neutrinos that are produced in the hot neutron star debris and/or magnetic fields. We will discuss here two possibilities: the neutrino-annihilation above the merger remnant as found in our simulations (supermassive neutron star plus disk) and a possible dramatic increase in the magnetic fields strength within the temporarily stabilized central object produced in the merger.


column density at t= 10.332 ms

column density at t= 12.852 ms

column density at t= 14.742 ms

Fig. 1. – Coalescence of binary neutron star system (both stars 1.4 $M_\odot$, tidal locking as initial spin state). Colour-coded is column density.

The calculations we refer to use a 3D smoothed particle hydrodynamics (SPH) with Newtonian self-gravity and gravitational wave back reaction forces. We use a temperature and composition dependent EOS and account for changes in the electron fraction and cooling due to neutrinos by a detailed multi-flavour neutrino scheme. Particular attention has been payed to the implementation of artificial viscosity: it is only present where needed, *i.e.* in shocks, and absent otherwise. For a detailed description of the numerical techniques we refer to Rosswog *et al.* (2000), Rosswog and Davies (2002), Rosswog and Liebendörfer (2003) and Rosswog *et al.* (2003).

2·1. *On the beaten track: annihilation of* $\nu_i\bar{\nu}_i$*-pairs.* – The remnants of a DNS merger radiate neutrinos at a total luminosity of $\sim 2\cdot 10^{53}$ ergs/s. The neutrino energies are between 10 and 25 MeV, the luminosities are clearly dominated by electron anti-neutrinos (Rosswog and Liebendörfer 2003). Similar results, but somewhat higher luminosities have been found by Ruffert and Janka (2001). Neutrino and anti-neutrinos annihilate above the merger remnant, yielding roughly elliptical contours of deposited energy per time and volume (see fig. 2, right column in Rosswog *et al.* 2003). It is the energy deposition per rest mass, η, that determines the asymptotic Lorentz-factor of the outflow. Guided by the typical duration of short GRBs we have assumed a deposition time, $\tau_{\rm dep} = 1$ s, to estimate $\eta = \frac{Q_{\nu\bar{\nu}}\tau_{\rm dep}}{\rho c^2}$, where $Q_{\nu\bar{\nu}}$ is the annihilation energy per time and volume. This is shown in fig. 2 for the case of the neutron star binary system whose evolution is shown in fig. 1. We find peak asymptotic Lorentz-factors of more than 10^4. This particular, initially corotating system is probably on the optimistic side as its large angular momentum yields a particularly broad funnel region above the central object. Nevertheless it shows that the neutrino annihilation mechanism has no problems in producing outflows with the required Lorentz-factors of several hundreds.
The total energy contained in the outflow, however, is substantially lower, $\sim 10^{48}$ – 10^{49} ergs, than the estimated isotropic energy equivalent of $\sim 10^{51}$ ergs, that is estimated for short GRBs at a redshift of about unity (*e.g.* Panaitescu *et al.* 2001). Therefore, the outflow has to be well-collimated in order to explain the above mentioned isotropic energy equivalent. Although well-collimated outflows occur in a large variety of astrophysical environments there is no generally accepted mechanism how this is achieved. At luminosities in excess of 10^{53} ergs/s the neutrinos emitted from the remnant will drive an energetic baryonic wind that will engulf the remnant. We have investigated to which extent this material can collimate the outflow (Rosswog and Ramirez-Ruiz, 2003). We find

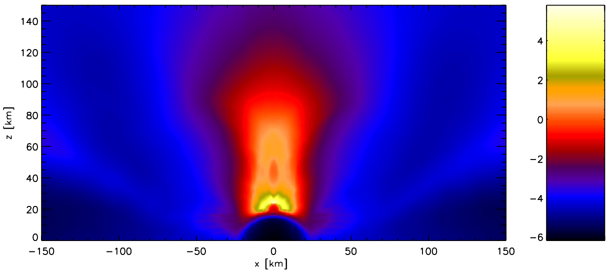


Fig. 2. – Colour-coded is the logarithm of the energy deposition per rest mass, $\log_{10}(\eta)$, from $\nu_i\bar{\nu}_i$-annihilation for the simulation shown in the previous figure. The quantity η determines the asymptotic Lorentz-factor, $\Gamma_{\rm asym} \approx \eta$.

that the result is quite sensitive to the total mass of the binary system, which governs the total neutrino luminosity. As the baryonic wind is sensitive to the neutrino luminosity, even a rather narrow distribution of DNS masses will result in a broad distribution of opening angles. We find typical opening angles of ~ 0.1 str, transforming into typical isotropized energies close to 10^{51} ergs (see fig. 3 in Rosswog and Ramirez-Ruiz, 2003). Recently, Aloy *et al.* (2004) have performed relativistic simulations to infer the launch of jets from DNS merger remnant disks. Their detailed simulations yield results in close agreement with our above estimates.

In summary, neutrino annihilation from DNS remnants seems to be able to launch relativistic jets with Lorentz-factors in excess of 100. The resulting outflows are relatively weak by GRB-standards, but with typical opening angles of about 0.1 str they yield isotropized energies in close agreement with the 10^{51} ergs that are inferred from observations.

2·2. *Off the beaten track: "hyper-magnetars"*. – In this section we want to discuss the possibility of a GRB being launched by a meta-stable, hyper-magnetized neutron star-like object. Further ideas about GRBs launched from strongly magnetized compact objects can be found in the literature (*e.g.*, Usov 1992, 1994, Duncan and Thompson 1992, Thompson and Duncan 1994, Mészáros and Rees 1997, Katz 1997, Kluzniak and Ruderman 1998 and Lyutikov and Blandford 2003).

The merger remnant harbors a central object of about 2.5 $M_\odot$, a mass that is beyond the maximum mass of most physical equations of state. Therefore, the central object will probably collapse at some stage to a black hole. Our hydrodynamic simulations (Rosswog and Davies 2002) show that the central object is rotating differentially, with periods from 0.3 ms to about 2ms from the center to the edge of the central object. As differential rotation can yield centrifugal support without mass shedding, it is very efficient in stabilizing configurations beyond their non-rotating upper mass limit.

The lifetime of the metastable central object depends on the time scale necessary to damp out the differential rotation. A discussion of these time scales and references can be found in Rosswog and Davies (2002). Although this question is far from being settled, we consider it plausible that the remnant remains stable for about a second, *i.e.* long enough for a short GRB. If so, this will open up possibilities to launch GRBs from the extreme, but probably short-lived magnetic fields in the central object (similar effects with down-scaled field strengths may still occur in the remnant disk, independent of whether the central object remains stable or not; for a comparison of the maximum field strengths across the merger remnant see fig. 8 in Rosswog *et al.* 2003).

Like in a proto-neutron star born in a supernova explosion, the neutrino emission from the remnant will build up entropy and lepton number gradients that will drive convective motion. If the rotation periods, $\tau_{\rm rot}$, are smaller than the convective overturn times, $\tau_{\rm conv}$, the remnant will support dynamo action. From our simulations we found a ratio, $Ro = \tau_{\rm rot}/\tau_{\rm conv}$ well below unity and therefore expect a dynamo to be active in the remnant. The field strength is expected to grow exponentially with an e-folding time close to the convective overturn time scale until it becomes buoyant. If initial neutron star field strengths of 10^{12} G are assumed, equipartition field strength ($> 10^{17}$ G) will be reached after only 40 ms, the field will then become buoyant and float up. If the whole rotational energy ($E_{\rm rot} \sim 8 \cdot 10^{52}$ erg) is transformed into magnetic field energy, the field strength, averaged over the central object, will be $\bar{B}_{co} \sim 3 \cdot 10^{17}$ G (still 10^{17} G, if only 10 % are transformed into magnetic energy). Owing to the hydrodynamic flow pattern within the central object, see fig. 8 in Rosswog and Davies (2002), we consider it most likely that the field will be wound up in local vortices up to equipartition field strengths and then will float up. Once it breaks through the remnant surface it will cause a sequence of relativistic blasts, the time structure of which will be governed by the fluid instabilities.

To estimate the time scale on which the central object will be spun down, τ_{sd}, we use the averaged field strength $\bar{B}_{co}$, the geometry found in the simulations and the magnetic dipole luminosity, $L_{\rm dp}$. We find $\tau_{sd} = E_{\rm rot}/L_{\rm dp} \approx 0.2\,{\rm s}$, very close to the typical duration of a short GRB.

3. – Summary

We have discussed possible pathways leading from the coalescence of a double neutron star system to the ultra-relativistic outflows that will later, far away from the central source, produce a (short-variety) GRB. In particular, we have addressed two mechanisms: the annihilation of $\nu_i\bar{\nu}_i$-pairs in the centrifugally cleaned pole regions above the merger remnants and the amplification of the initial neutron star magnetic fields via a convective dynamo inside the temporarily stabilized central object of the remnant.

We find that the $\nu_i\bar{\nu}_i$-annihilation will drive bipolar, relativistic jets with large Lorentz-factors (in extreme cases beyond 10^4). The total energies within these jets are moderate by GRB-standards, $\sim 10^{48} \cdots 10^{49}$ ergs, but due to the interaction with baryonic material that has been blown off the remnant via the intense neutrino radiation, these outflows are typically collimated into half-opening angles of about 0.1 str. An observer would infer isotropized luminosities of about 10^{51} ergs.

We consider it to be very plausible that the central object in the remnant is stabilized by differential rotation for long enough to launch a GRB before collapsing to a BH. If it remains stable for a good fraction of a second then the initial neutron star magnetic fields are expected to be amplified by a low-Rossby number $\alpha - \Omega$-dynamo. In principle, enough rotational energy is available to attain an average field strength in the central object of $3 \cdot 10^{17}\,{\rm G}$. Locally the equipartition field strength (ranging from 10^{16} to a few times $10^{17}\,{\rm G}$ depending on the exact position in the remnant) may be reached. This will cause the corresponding fluid parcels to float up and produce via reconnection an erratic sequence of ultra-relativistic blasts. In addition, the central object can act as a "super-pulsar" of $\sim 10^{17}\,{\rm G}$ that transforms most of its rotational energy into an ultra-relativistic wind with frozen-in magnetic field. As shown in Usov (1994) such a wind will result in a black-body component plus synchro-Compton radiation. Such a super-pulsar will spin-down in $\sim 0.2\,{\rm s}$, just the typical duration of a short GRB.

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