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Going out with a bang: compact object collisions resulting from supernovae in binary systems

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ABSTRACT

Binary star systems containing a neutron star or a black hole with an evolved, massive star are dynamically perturbed when the latter undergoes a supernova explosion. It is possible that the natal kick received by the newly formed neutron star in the supernova may place the stellar remnants into a bound, highly eccentric orbit. In this case, the two compact objects can tidally interact and spiral into one another on a short time-scale. The interaction with an accretion disc of supernova debris is also considered. We quantify the likelihood of such events and show that they would be expected to produce a high-energy transient, possibly a short gamma-ray burst, typically within a few days of the supernova.

Key words: black hole physics – binaries: general – stars: neutron – supernovae: general – gamma rays: bursts – X-rays: bursts.

1 INTRODUCTION

The *coalescence* of a neutron star–neutron star (NS–NS) binary under the action of gravitational wave emission is arguably the leading progenitor model for short gamma-ray bursts (GRBs; e.g. Eichler et al. 1989; Meszaros & Rees 1992; Narayan, Paczynski & Piran 1992; Ruffert & Janka 1997; Rosswog, Ramirez-Ruiz & Davies 2003; Oechslin & Janka 2006). *Collisions* between two neutron stars also do occur, for instance in regions of large stellar number densities, but at a substantially lower rate. Katz & Canel (1996) suggested that such events might be the central engines of short GRBs.

In gravitational wave-driven coalescences the extremely large sound velocities in nuclear matter, $c_s \sim 0.4c$, result in subsonic initial encounters, and shocks only form in later phases after rotationally shed material interacts with itself and with the central object (Ruffert & Janka 2001; Rosswog & Davies 2002, in particular their fig. 13). In stark contrast, direct collisions of two neutron stars approach each other with relative velocities close to free-fall, $v_{\rm free-fall} \approx 0.64c\, (\frac{M}{2.8\,{\rm M}_{\odot}})^{1/2}(\frac{20\,{\rm km}}{R_1+R_2})^{1/2}$, and therefore produce strong shocks passing through the nearly unperturbed initial neutron stars. Ruffert & Janka (1998) found that these shocks seriously pollute the direct collision vicinity with large amounts of baryonic material, which led them to rule out direct neutron star collisions as GRB progenitors. However, prospects for producing a GRB may be enhanced for off-centre collisions, which largely avoid these very strong shocks, and for systems in which one of the neutron stars is replaced by a black hole (BH).

Interest in such collisions has been rekindled by the observation of prolonged central engine activity in some short GRBs. Though their nature is still under debate, features such as X-ray flares (Burrows et al. 2005) or long soft tails of emission (Barthelmy et al. 2005; Norris & Bonnell 2006) suggest continued energy injection. A promising mechanism to power the observed late-time activity is the fallback accretion of the NS debris (Faber et al. 2006; Rosswog 2007), and this effect could be enhanced in collisional encounters (Lee & Ramirez-Ruiz 2007).

Collisions and close encounters between compact objects occur predominantly in regions of high stellar density, such as the cores of globular clusters (e.g. Hills & Day 1976; Leonard 1989; Freitag & Benz 2005) or the central clusters of massive compact remnants that are expected in the centres of galaxies (e.g. Alexander 2005). This problem has been addressed in a number of previous studies (Katz & Canel 1996; Hansen & Murali 1998). In this paper, we investigate an alternative possibility of compact object collisions induced by supernovae (SNe) in binary star systems. We consider binary systems initially composed of two massive ($>8\,{\rm M}_{\odot}$) main-sequence (MS) stars. The primary, i.e. the more massive star, leaves the MS and explodes as an SN, giving birth to the first compact object, either an NS or a BH. If the binary system does not get disrupted, we are left with a massive MS star in orbit around an NS (or a BH). Since the primary loses most of its envelope mass prior to the SN and the secondary is itself a massive star, there is a high probability for the binary to survive the explosion (e.g. van den Heuvel & Heise 1972; Portegies Zwart & Verbunt 1996). The life of the secondary star will soon come to an end. Low-mass He

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stars in wide orbits ($P_{\rm orb} > 0.25$ d) and those more massive than $\sim$4 M$_\odot$ do not go through common envelope evolution (Dewi & Pols 2003) and the system will undergo the second SN explosion. At this point, either (1) the binary disrupts, (2) the binary survives as an NS–NS or an NS–BH or (3) the newly formed NS is placed in a nearly parabolic orbit with a pericentre distance comparable to its tidal radius. In the last case, we expect the NS to tidally interact with the companion compact object and rapidly spiral into it. This is the scenario considered here.

Following the second SN, a debris disc could form around the newborn NS (Chevalier 1989; Lin, Woosley & Bodenheimer 1991; Zhang, Woosley & Heger 2008). Such discs are thought to be short-lived systems ($\tau_{\rm disc} \lesssim 10^5$ yr; Ekşi, Hernquist & Narayan 2005; Wang, Chakrabarty & Kaplan 2006b); therefore, they have no influence on NS–NS mergers ($\tau_{\rm merge} \sim$ Gyr) or collisions in globular clusters. However, in our case the two compact objects will undergo a close encounter within days of the explosion and the presence of a fallback disc may have a significant effect on the event (Popov 2006).

This paper is organized as follows. In Section 2, we investigate whether collisions induced by an asymmetric SN are feasible and how they depend on the binary parameters (eccentricity, orbital period, pre-SN mass, SN kick). In Section 3, we derive the delay time between the precursor SN and the NS encounter. The presence of a debris disc around the newborn NS is addressed in Section 4. We discuss our results and summarize our conclusions in Section 5.

2 PROBABILITY OF A COLLISION

We consider a binary system which already experienced a first SN explosion and make two assumptions: (1) the system survived the explosion and now consists of a compact remnant and the remaining massive star and (2) it is in a circular orbit prior to the second SN.

The geometry of the system is illustrated in Fig. 1: we adopted a reference frame centred on the exploding star of mass M_1, and where the NS, of mass M_{NS}, is at rest. The star is moving in a circular orbit, with separation a_0 and velocity $V_{\rm orb} = (GM_0/a_0)^{1/2}$, where

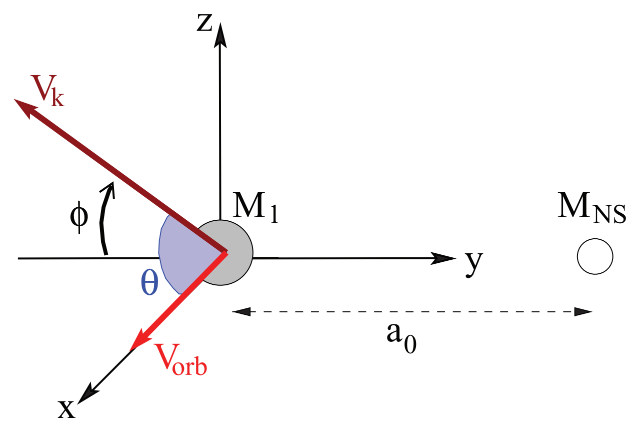

Figure 1. Geometry of the system: the reference frame is centred on the exploding star of mass M_1. The NS is at rest, while the star is moving in a circular orbit, with separation a_0 and relative velocity $V_{\rm orb}$. The pre-SN orbit lies in the x–y plane, perpendicular to the plane of the page. The angle θ is defined as the angle between the pre-SN orbital velocity $V_{\rm orb}$ and the kick velocity $V_{\rm k}$, imparted by the SN explosion. The angle ϕ is defined as the angle between the pre-SN orbital plane and the plane containing $V_{\rm orb}$ and $V_{\rm k}$.

G is the gravitational constant and $M_0 = M_1 + M_{\rm NS}$ the total mass of the system.

The direction of the kick is specified by the two angles θ and ϕ, respectively. As shown in Fig. 1, we defined θ as the angle between the pre-SN orbital velocity $\boldsymbol{V}_{\rm orb}$ and the kick velocity $\boldsymbol{V}_{\rm k}$, imparted by the SN explosion. The angle ϕ is defined as the angle between the pre-SN orbital plane and the plane containing $\boldsymbol{V}_{\rm orb}$ and $\boldsymbol{V}_{\rm k}$, where $\phi = 0$ ($\phi = \pi$) if $\boldsymbol{V}_{\rm k}$ lies in the pre-SN orbital plane and points outwards (towards) the NS and $\phi = \pi/2$ ($\phi = 3\pi/2$) if the plane containing $\boldsymbol{V}_{\rm orb}$ and $\boldsymbol{V}_{\rm k}$ is perpendicular to the pre-SN orbital plane and $\boldsymbol{V}_{\rm k}$ has a Cartesian component parallel (antiparallel) to the pre-SN angular momentum. If the kick velocity has no preferential orientation, then the values of $\cos\theta$ and ϕ have an equal probability of lying in the range $[-1, 1]$ and $[0, 2\pi]$, respectively.

To study the effects of the second SN, we made the standard assumption that the SN mass loss and kick are instantaneous (i.e. on a time-scale shorter than the orbital period) and neglected the impact of the expanding SN shell on the compact object companion, which have little or no effect on the binary evolution (Fryxell & Arnett 1981; Kalogera 1996). The specific angular momentum of the system is given by

$$|\boldsymbol{r} \times \boldsymbol{V}| = \left[GM_f\, a(1-e^2)\right]^{1/2}, \qquad (1)$$

where $\boldsymbol{r} = (0, a_0, 0)$ soon after the SN and $\boldsymbol{V} = \boldsymbol{V}_{\rm orb} + \boldsymbol{V}_{\rm k}$ is the resultant velocity of the newborn compact object. On the right-hand side, $M_{\rm f}$ is the final mass of the system and a and e are the post-SN orbital separation and eccentricity, respectively. In the following, we consider the simplest case of two identical NSs (same mass and radius).

In order to induce a collision, the post-explosion orbit must have a pericentre radius $R_{\rm p} = a(1-e)$ comparable to the NS radius $R_{\rm NS} \approx 10\,{\rm km} \ll a_0$. Therefore, only nearly parabolic orbits with eccentricity $e \gtrsim 1 - 2R_{\rm NS}/a_0 \approx 1$ may lead to such an encounter. From equation (1), it follows that the kick velocity must be such that it significantly reduces the orbital angular momentum of the system. This may happen (1) if the kick velocity is much higher than the pre-SN orbital velocity, so that $\boldsymbol{V} \sim \boldsymbol{V}_{\rm k}$, and directed in the radial direction, or (2) if the kick velocity is comparable in magnitude with the pre-SN orbital velocity but directed in the opposite direction, so that $\boldsymbol{V} \sim \boldsymbol{0}$.

In the former case ($V_{\rm k} \gg V_{\rm orb}$) the kick will unbind the binary, and the newborn NS will collide with the companion only if the kick direction points exactly towards it. The probability of such alignment is small, $p_{\rm coll} \sim R_{\rm NS}/a_0 < 10^{-8}$. Furthermore, such high values of $V_{\rm k}$ are very unlikely to occur as they would imply an unfeasibly large population of isolated NSs for every observed binary pulsar.

A collision between the two compact objects takes place only if the following constraints on θ and ϕ, derived from equation (1), are fulfilled:

$$\sin^2\phi \leqslant \frac{\xi^2 - \left[1 + \left(\frac{V_{\rm k}}{V_{\rm orb}}\right)\cos\theta\right]^2}{\left(\frac{V_{\rm k}}{V_{\rm orb}}\right)^2 \sin^2\theta} \qquad (2)$$

$$-\frac{V_{\rm orb}}{V_{\rm k}}(1+\xi) \leq \cos\theta \leq -\frac{V_{\rm orb}}{V_{\rm k}}(1-\xi), \qquad (3)$$

where

$$\xi = \left(4\frac{M_{\rm f}}{M_0}\frac{R_{\rm NS}}{a_0}\right)^{1/2} \ll 1. \qquad (4)$$

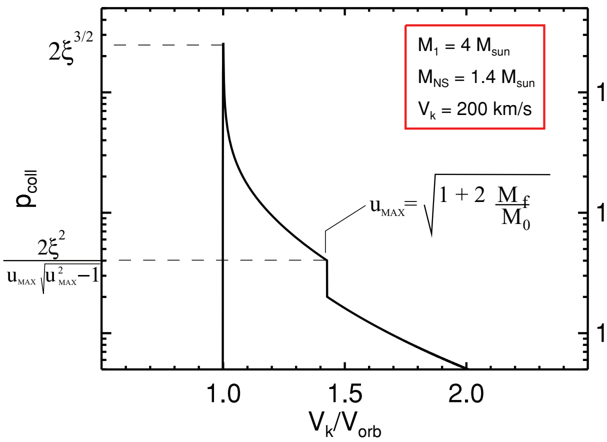

Figure 2. Probability of a collision as a function of the ratio V_k/V_{orb} between the kick velocity and the pre-SN orbital velocity. For a given mass loss, the final orbit is bound if $V_k/V_{orb} < u_{max}$. The values of p_{coll} reported on the right y-axis have been calculated for a kick magnitude $V_k = 200\,km\,s^{-1}$, a pre-SN mass $M_1 = 4\,M_\odot$ and an NS mass of $1.4\,M_\odot$.

It immediately follows from equation (3) that if $V_k < V_{orb}$ a close encounter is not possible, since $\cos\theta \geq -1$, and that the minimum kick magnitude to induce a collision is $V_k = V_{orb}(1-\xi) \approx V_{orb}$. For isotropic kicks, we derived the probability of a collision, p_{coll}, as a function of V_k by numerically integrating the following expression:

$$p_{coll}(V_k) = \frac{1}{\pi}\int_{\theta_{max}(V_k)}^{\theta_{min}(V_k)} d\theta \sin\theta \int_0^{\phi_{max}(V_k,\theta)} d\phi, \quad (5)$$

where the integration limits on ϕ and θ are set by equations (2) and (3), respectively. The result is shown in Fig. 2. The values of p_{coll}, quoted on the right y-axis, have been calculated for a kick magnitude $V_k = 200\,km\,s^{-1}$, a pre-SN mass $M_1 = 4\,M_\odot$ and an NS mass $M_{NS} = 1.4\,M_\odot$.

The probability shows a narrow peak at $V_k/V_{orb} = 1$ with a maximum value of $p_{coll} \sim 2\xi^{3/2}$ and then decreases rapidly. At $V_k/V_{orb} = u_{max}$, with u_{max}=$(1+2M_f/M_0)^{1/2}$, the probability drops by a factor of 2. In fact, for a given mass loss, highly eccentric post-SN orbits are still bound only if $V_k/V_{orb} < u_{max}$, while higher values of V_k disrupt the system. In the latter case, the two compact objects collide only if V_k has a Cartesian component directed towards the companion NS, i.e. only if $\pi/2 < \phi < 3\pi/2$.

If the first born compact object is a BH, rather than an NS, then the pericentre radius R_p must be comparable to the NS tidal radius, $R_{tid} \simeq R_{NS}(M_{BH}/M_{NS})^{1/3}$, in order for the two objects to interact. In addition, the condition $R_p > R_g$, where R_g is the BH gravitational radius, avoids the possibility of the NS being swallowed directly by the BH. The latter constraint excludes BHs more massive than $\sim 10\,M_\odot$, while for less massive BHs the probability would change by a factor $\approx (M_{BH}/M_{NS})^{1/4} - (M_{BH}/5\,M_\odot)^{3/4}$ for a similar value of mass loss.

2.1 Natal kicks

Here we assume that kick velocities follow the birth velocity distribution of isolated radio pulsars. The probability of an NS–NS collision is therefore given by the convolution of the probability $p_{coll}(V_k)$, derived in equation (5), with the kick velocity distribution $f(V_k)$:

$$P_{coll} = \int_0^\infty p_{coll}(V - V_k) f(V_k)\, dV_k. \quad (6)$$

Arzoumanian, Chernoff & Cordes (2002) modelled the kick distribution as two Gaussian components having characteristic dispersions $\sigma_l \sim 90\,km\,s^{-1}$ and $\sigma_h \sim 500\,km\,s^{-1}$. From a larger sample of 73 young (<3 Myr) pulsars, Hobbs et al. (2005) derived a mean three-dimensional birth velocity of $\sim$400 km s^{-1} with a characteristic dispersion $\sigma \sim 265\,km\,s^{-1}$. The expression in equation (6) has been numerically integrated for both a bimodal distribution, as in Arzoumanian et al. (2002), and a broad Maxwellian distribution, as in Hobbs et al. (2005). Results are shown in Fig. 3, which reports the probability of an NS–NS collision as a function of the pre-SN orbital period. Calculations have been performed for a pre-SN mass of $4\,M_\odot$ (solid lines) and $10\,M_\odot$ (dashed lines).

In order to obtain the distribution of post-SN orbital characteristics (velocity, separation, eccentricity), we ran Monte Carlo simulations of an SN explosion in a circular binary system. We derived the effects of an SN on the dynamics of a binary according to the analytic formulation of Tauris & Takens (1998) and the kick direction and magnitude by Monte Carlo techniques. We assumed an isotropic distribution of kicks ($P_\phi = 1/2\pi$, $P_\theta = \sin\theta/2$) and drew the kick magnitude from both the bimodal and the Maxwell distributions of speeds used in our previous calculations. For each binary system, we ran 10^8 simulations and estimated the probability of a collision as the fraction of simulated SN explosions which lead to an encounter ($R_p \lesssim 2R_{NS}$). In Fig. 3, the results of the simulations are shown as filled squares (Maxwell distribution) and circles (bimodal distribution) overlaid on the solution to equation (6). The good agreement between the two confirms our analytic derivation.

Throughout this work, we assumed that kicks are isotropically distributed and uncorrelated with the binary properties; however, this is a major source of uncertainty. Several physical mechanisms have been proposed to explain observations of high-velocity pulsars (Lai 2001; Wang, Lai & Han 2006a, and references therein) and, for instance, some of them invoke a coupling between the direction

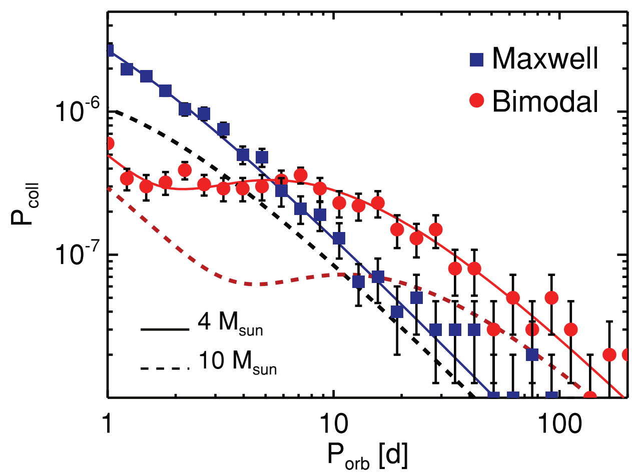

Figure 3. Probability of an NS–NS collision as a function of the pre-SN orbital period P_{orb}, calculated for a pre-SN He star mass of $4\,M_\odot$ (solid lines) and $10\,M_\odot$ (dashed lines). The NS mass is $1.4\,M_\odot$. Symbols report the results of numerical simulations: we assumed an isotropic distribution of kick directions and ran simulations for both a bimodal distribution (red circles) and a Maxwellian distribution (blue squares) of kick speeds. We restricted ourselves to the case in which the binary orbit is circular prior to the second SN.

of the kick and the stellar spin prior to the explosion (Wang, Lai & Han 2007).

Fig. 3 shows that the probability of a collision event is higher in close binary systems ($P_{\rm orb} < 10$ d). In such close systems, the presence of a binary companion can profoundly alter stellar evolution. It seems conceivable that it may somehow affect the SN explosion and the kick imparted to the stellar remnant (e.g. Pfahl et al. 2002; Podsiadlowski et al. 2004). Tidal distortion, aspherical stellar winds and fast rotation, which in close binaries tends to be aligned to the orbital spin, cause asymmetries in the star density and velocity distributions. The coupling between the stellar envelope and its core during the explosion is not yet understood, but one might expect that it can lead to an asymmetric mass ejection, hence imparting a recoil velocity which is correlated with the orbital motion.

The probability of an encounter would significantly change according to the kick geometry. If natal kicks are preferentially in the direction of the pre-SN orbital angular momentum, then the close encounters described here would not happen. By contrast, if the preferential direction is along the orbital plane in a cone with semi-aperture $\Delta\alpha$, the number of collisions would increase by a factor $\sim\pi/2\Delta\alpha \lesssim \xi^{1/2}$.

3 DELAY SINCE THE SUPERNOVA

These collisions are triggered by an asymmetric SN explosion and will happen soon after it. The time interval Δt that elapses since the SN can be derived from the known orbital parameters is

$$\Delta t = \sqrt{\frac{a^3}{GM_{\rm f}}}\left[\frac{\pi}{2} - \arcsin\left(\frac{1-\frac{a_0}{a}}{e}\right) + \sqrt{-\left(\frac{a_0}{a}\right)^2 + 2\frac{a_0}{a} - (1-e^2)}\right], \quad (7)$$

where the post-explosion eccentricity e and separation a have been calculated for each simulated SN following the recipes of Tauris & Takens (1998). If the newborn NS is shot in the direction opposite to the companion ($\phi \sim 0$) but still bound, it will cover almost the entire orbit before the encounter; in this case, the delay will be $\sim 2\pi\sqrt{\frac{a^3}{GM_{\rm f}}} - \Delta t$.

For hyperbolic orbits ($e \gtrsim 1$), we consider only those cases in which the NS is launched towards the companion ($\phi \sim \pi$). The elapsed time since the explosion is

$$\Delta t_{\rm hyp} = \sqrt{\frac{a^3}{GM}}\ln\left\{\left[1 + \frac{a_0}{a} + \sqrt{\left(\frac{a_0}{a}\right)^2 + 2\frac{a_0}{a} - (e^2-1)}\right]\right\}. \quad (8)$$

Fig. 4 shows the cumulative distribution of delays (left-hand panel) and penetration factors $\beta = 2R_{\rm NS}/R_{\rm p}$ (right-hand panel) for the simulations described in Section 2.1. The pre-SN mass of the He star was fixed at $4\,{\rm M}_{\odot}$, but the distributions presented in Fig. 4 do not depend on this particular choice. In fact, the SN mass loss mainly affects the normalization of the probability curve rather than its shape (see Fig. 3).

As shown in Fig. 4 (left-hand panel), most of the collisions happen a few days after the SN. Though the events are nearly simultaneous, the SN will be detectable only a couple of weeks later, when it reaches its maximum optical luminosity (shadowed area). Only a small fraction ($\lesssim$5 per cent) of events happen at later times ($\Delta t >$ 30 d). Off-axis collisions, which could more easily avoid a large baryonic contamination, are dominant ($\sim$80 per cent with $\beta < 2$; Fig. 4, right-hand panel), while head-on collisions ($\beta \gg 1$) are rare events ($<$5 per cent).

4 THE EFFECT OF A FALLBACK DISC

In an SN, some of the mass is expected to remain bound to the central object and carry sufficient angular momentum to settle into a disc (Michel 1988; Lin et al. 1991; Woosley 1993). The presence of such discs around NSs has been invoked to explain the peculiar class of anomalous X-ray pulsars (AXPs), and indeed the first observational evidence of their existence has been discovered around the AXP 4U 0142+61 (Wang et al. 2006b). Yet it is unclear whether this disc is passive (Wang et al. 2006b) or affects the properties of the newly formed NS (Ertan et al. 2007). Instead, if a fallback disc persists after an SN in a binary system, as considered here, it may drastically increase the cross-section of an interaction event.

Numerical simulations of stellar evolution find that the specific angular momentum distribution ranges from $j \sim 10^{14}$–10^{15} cm^2 s^{-1}

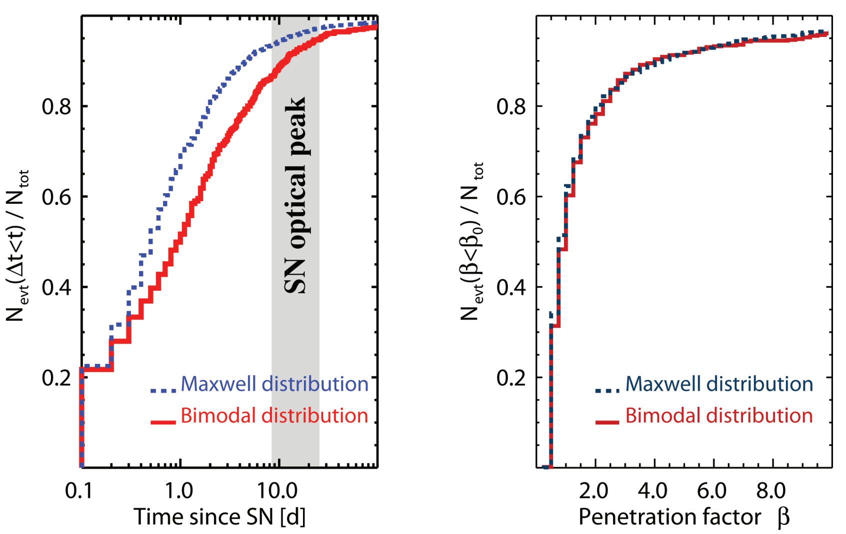

Figure 4. Left-hand panel: cumulative distribution of delay times since the SN explosion; the shadowed region indicates the time interval of the SN peak. Right-hand panel: cumulative distribution of penetration factors, β, defined as the ratio of the sum of the NS radii to the post-SN pericentre distance, $\beta = 2R_{\rm NS}/R_{\rm p}$.

(in the stellar core) to $j \gtrsim 10^{17}\,\mathrm{cm^2\,s^{-1}}$ (in the outer layers) prior to the explosion (Heger, Woosley & Spruit 2005). The SN shocks traversing the star likely induce an extensive mixing between the stellar layers, and an appreciable fraction of fallback material may have an angular momentum as high as $j \sim 10^{17}\,\mathrm{cm^2\,s^{-1}}$. By assuming that conservation of angular momentum holds during the collapse, this sets the initial size of the fallback disc $R_{\mathrm{NS}} < R_{\mathrm{d}} < 10^8$ cm. For typical values of natal kicks ($<1000\,\mathrm{km\,s^{-1}}$; Chatterjee et al. 2005), the disc is not left behind, but remains bound to the newborn NS. The system is therefore composed of an NS (or a BH, formed in the first SN explosion) and a newborn NS (formed in the second SN) surrounded by a fallback disc.

After an initial transient phase, the disc spreads to larger radii as $R_{\mathrm{d}} \propto (t/\tau_\nu)^{3/8}$, where $\tau_\nu \approx 10^3$–10^4 s is the local viscous time-scale (Lynden-Bell & Pringle 1974; Cannizzo, Lee & Goodman 1990; Menou, Perna & Hernquist 2001), and reaches a size of $\sim 10^9$ cm at 30 d since the SN. The chance for the disc to interact with the stellar companion shortly after the second SN is therefore $\propto (R_{\mathrm{d}}/R_{\mathrm{NS}})^{3/4} \gtrsim 100$ times higher than the probability of a direct collision derived in Section 2. The perturbation induced by the passage of the first NS through the disc extends up to the NS accretion radius $r_{\mathrm{a}} = GM_{\mathrm{NS}}/v_{\mathrm{rel}}^2 \approx R_{\mathrm{d}}$, where v_{rel} is the relative velocity between the disc and the first NS. This is comparable with the disc radius itself and therefore most of the mass in the disc ($10^{-6}\,\mathrm{M_\odot} \lesssim M_{\mathrm{d}} < 0.1\,\mathrm{M_\odot}$; Chevalier 1989; Lin et al. 1991; Fryer 2009) is transferred to the NS on a dynamical time-scale of $\sim 2(R_{\mathrm{d}}/10^9\,\mathrm{cm})^{3/2}$ s. This episode of accretion may result in a luminous X-ray outburst a few days/weeks after an SN. The precise nature of this outburst depends on the details of the interaction and the associated gas dynamics but it is highly likely to involve accretion rates close to Eddington.

The presence of a debris disc in a binary system may also lead in some cases to a rapid shrinkage of the orbit and speed up the merger of the two objects (Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Armitage & Natarajan 2002). For fallback discs of mass $M_{\mathrm{d}} \ll 0.1\,\mathrm{M_\odot}$, the characteristic time-scale of this process is $\tau_{\mathrm{shrink}}/\tau_\nu \gtrsim (M_{\mathrm{d}} + M_{\mathrm{NS}})/M_{\mathrm{d}} \gg 1$ (Lodato et al. 2009). The effects of such an interaction are not likely to be important since, as pointed out above, most of the disc mass is transferred to the NS companion on a much shorter time-scale.

5 SUMMARY AND DISCUSSION

We showed in Section 2 that an SN may be followed by the collision of two compact objects. A close encounter requires the explosion to be asymmetric (spherical explosion always led to an expansion of the orbit) and happens only for a narrow range of kick magnitudes and directions, namely when the kick velocity is comparable to the pre-SN orbital velocity and opposite in direction. These events are therefore expected to be rare.

Similar to mergers, collisions of compact objects end up forming an accretion disc/BH system (Lee & Ramirez-Ruiz 2007), as commonly invoked as the central engine powering GRBs. One of the most important open issue related to (all) the GRB central engines is the ‘baryonic contamination’ problem (Piran 1999, and references therein): how can a violent explosive event involving a few solar masses of baryons channel a huge amount of energy into a region that is almost completely baryon-depleted? The popular answer to this question in the context of *NS mergers* has been the centrifugally evacuated funnel region that forms above the poles of the central remnant (e.g. Davies et al. 1994; Rosswog et al. 2000; Ruffert & Janka 2001), although it had been realized relatively early on that this loophole could possibly be threatened by the ablation of baryonic material via the extreme neutrino luminosities of $\sim 10^{53}\,\mathrm{erg\,s^{-1}}$ (Ruffert & Janka 1999; Rosswog & Ramirez-Ruiz 2002). The first calculations that account for neutrino-heating processes in an NS merger remnant (Dessart et al. 2009) seriously downsize this loophole. For at least as long as the central, super-massive NS has not collapsed into a BH, the remnant drives a very strong baryonic wind ($\dot{\mathrm{M}}_{\mathrm{w}} \sim 10^{-3}\,\mathrm{M_\odot\,s^{-1}}$) into exactly the above mentioned funnel region, making the launch of a relativistic outflow impossible. This conclusion may need modification once a BH forms.

For the case of *NS collisions,* the situation is even less promising. At least head-on collisions ($\beta \gg 1$) with their violent shocks heavily spoil their surroundings with baryonic material even if neutrino-driven winds are disregarded (Ruffert & Janka 1997). However, we have shown that only a small fraction (<5 per cent) of collisions are expected to be near-central (cf. Fig. 4, right-hand panel), while most of them are off-centre. In this case, the outcome may be more favourable to GRBs. Off-centre collisions lead to much weaker shocks, and a much smoother subsequent coalescence, likely dispersing a substantial amount of debris material in highly eccentric orbits. This material in turn can produce late-time X-ray flares similar to those seen in GRBs (Lee & Ramirez-Ruiz 2007; Rosswog 2007). Collisions between a stellar-mass BH and an NS are even more likely to produce a short GRB since they avoid two problems from the beginning: there will only be moderate shocks in the disc formation phase after the disruption and there is never a hot, massive NS as a major source for the neutrino wind. So, in the latter cases, it may be possible to drive the ultra-relativistic outflow to power a short-duration GRB.

In the case of NS collisions induced by an SN explosion, for a GRB to occur the emerging jet must have a minimum power to break out of the remnant layers maintaining a high Lorentz factor (MacFadyen, Woosley & Heger 2001; Matzner 2003; Zhang, Woosley & Heger 2004). This condition is particularly restrictive when the delay time between the SN and the collision event is short ($t \ll 1$ d). As the supernova remnant (SNR) expands, the requirements on the jet energy and beaming angle decrease; therefore, even low luminosity and less collimated jets could pass this constraint. Furthermore, if the SNR radius is larger than the radius for internal shocks ($R_{\mathrm{IS}} \approx 10^{12}$–$10^{13}$ cm), then the prompt GRB emission can plausibly occur within it, as the precursor SN has the advantage of cleaning the circumburst environment from baryon pollution (Vietri & Stella 1998), thus favouring a relativistic expansion of the GRB jet within the remnant. A major problem for longer time delays is whether the GRB emission can be observed or it is obscured by the dense SNR shell. In fact, for a radial velocity of the ejecta $v_{\mathrm{ej}} \sim 10^4\,\mathrm{km\,s^{-1}}$, the SNR radius is $R \sim 10^{14}$ cm after 1 d and the resulting column density is $n_{\mathrm{H}} \sim 10^{28}\,(M_{\mathrm{shell}}/\mathrm{M_\odot})\,\mathrm{cm^{-2}}$.

Both these problems (the jet break-out and the SNR optical thickness) are not present if the geometry of the SNR shell is not spherical, but anisotropic either because of an asymmetric explosion (Leonard et al. 2006; Maeda et al. 2008) or because it is subject to hydrodynamic instabilities (Chevalier, Blondin & Emmering 1992; Blondin & Ellison 2001). The SNR might not interfere with the jet and the GRB emission may escape from underdense regions. In this case, a short GRB (or an X-ray outburst, see Section 4) could follow the SN explosion. In contrast to long GRBs, connected to the peculiar broad-line Type Ic SNe (Woosley & Bloom 2006), bursts originated through this channel will be associated with any type of core-collapse SN. The SN always precedes the close encounter of the NSs, but according to the distribution of delay times shown in Fig. 4 the high-energy transient should be observed first, while the

SN emission will be visible a few days later. For small kick velocities, a longer delay between the SN and the collision of NSs is also possible: ∼10 per cent of our events happen a couple of weeks after the stellar collapse and a small fraction, <5 per cent, happens more than one month later.

According to the proposed scenario, double NSs and close encounters have the same progenitor systems, i.e. a massive binary system which undergoes two SN explosions. A fraction of NS–NS binaries will merge within a Hubble time-scale, giving birth to a short GRB (Eichler et al. 1989). By assuming that the main progenitors of short GRBs are binary mergers (either NS–NS or NS–BH), the observed rate of collisions $\dot{n}_{\rm coll}^{\rm obs}$ is simply proportional to the rate of short GRBs $\dot{n}_{\rm SGRBs}$:

$$\dot{n}_{\rm coll}^{\rm obs} = f_{\theta_{\rm c}} \dot{n}_{\rm coll} = \frac{n_{\rm coll}}{n_{\rm mergers}} \; f_{\theta_{\rm m}} \; \dot{n}_{\rm SGRBs}, \quad (9)$$

where $f_{\theta_{\rm c}}$ and $f_{\theta_{\rm m}}$ are the beaming corrections for bursts produced through collisions and mergers, respectively, and $n_{\rm coll}/n_{\rm mergers}$ is the relative strength of the two channels, the former giving rise to prompt collisions and the latter leading to merging NSs. Following the method described in Kalogera & Lorimer (2000), we derived an upper limit of $n_{\rm coll}/n_{\rm mergers} \lesssim 10^{-3}$. With a full-sky rate of ∼170 short GRBs per year, as derived from the Burst And Transient Source Experiment (BATSE) GRB Catalogue,[1] and by assuming the same beaming factor of short GRBs originated from double NSs ($f_{\theta_{\rm c}} = f_{\theta_{\rm m}}$), we estimated for our events an observed rate of $\lesssim 0.2$ yr^{-1}. This number increases by more than a factor of 10^3 when considering the interaction with a disc of SN debris, which may produce a luminous X-ray outburst.

A wealth of new transient phenomena is to be discovered in the near future, when the sky will be continuously monitored both at high energies (e.g. *Swift, Fermi, MAXI*) and at optical/NIR wavelengths (e.g. *PAN-STARRS, LSST*). Collisions induced by an SN explosion, though rare, might be detected by forthcoming surveys. Such events will be located in young stellar environments, such as stellar star clusters or star-forming galaxies, or likely at redshift $z \gtrsim 1$, when the star formation rate had its maximum (e.g. Madau & Pozzetti 2000; Hopkins & Beacom 2006). Though so far short GRBs have been found at moderately low redshifts $\langle z \rangle \sim 0.5$ and in regions of low/moderate star formation, we note that in the growing sample of GRBs with known redshifts a few bursts, characterized by a rather short intrinsic duration (e.g. 090426 at $z = 2.6$; Levesque et al. 2009), may have originated from the direct collisions described in this paper.

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[1] http://www.batse.msfc.nasa.gov/batse/grb/catalog/

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