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BLACK HOLE–NEUTRON STAR MERGERS

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RESUMEN

Presentamos un estudio numérico de la interacción hidrodinámica en una binaria compacta formada por un agujero negro y una estrella de neutrones, cuando la separación es del orden del radio de la estrella. Utilizamos un formalismo Lagrangiano con un programa Newtoniano de hidrodinámica de partículas en tres dimensiones. El agujero negro se modela como una masa puntual con una frontera absorbente en el radio de Schwarzschild. Las condiciones iniciales corresponden a binarias irrotacionales en equilibrio, y simulamos la evolución del sistema durante aproximadamente 23 ms. El resultado de la interacción depende fuertemente de la compresibilidad del gas, y se forma un disco de acreción alrededor del agujero negro, conteniendo algunas décimas de masa solar. Al mismo tiempo, hasta 0.1 masas solares son eyectadas del sistema. Nuestros resultados muestran que estos sistemas son buenos candidatos para la producción de destellos de rayos gamma.

ABSTRACT

We present a numerical study of the hydrodynamics in the final stages of inspiral in a black hole–neutron star binary, when the separation becomes comparable to the stellar radius. We use a Newtonian 3D Smooth Particle Hydrodynamics (SPH) code and model the neutron star with a stiff equation of state. The black hole is modeled as a point mass with an absorbing boundary at the Schwarzschild radius. The initial conditions correspond to irrotational binaries in equilibrium, and we follow the evolution of the system for approximately 23 ms. We find that the result of the initial interaction between the stars is an intense episode of mass transfer, and the details of the subsequent evolution depend greatly on the assumed stiffness of the equation of state. We find that an accretion disk containing a few tenths of a solar mass is formed around the black hole, and that up to 0.1 solar masses of material may be dynamically ejected from the system. Our results show that these systems are promising candidates for the production of short gamma–ray bursts.

Key Words: **BINARIES: CLOSE — GAMMA RAYS: BURSTS — HYDRODYNAMICS — STARS: NEUTRON**

1. INTRODUCTION AND MOTIVATION

Compact binary systems, such as PSR 1913+16 (Hulse & Taylor 1975), PSR 1534+12 (Wolszczan 1991), both double neutron star binaries, are driven to coalesce in less than the Hubble time due to the emission of gravitational waves. There are no observed black hole–neutron star systems yet, but it is believed that they do in fact exist. Estimates of the event rates can be inferred from the statistics of Hulse–Taylor type systems and from theoretical studies of stellar evolution, and are expected to be about 10^{-6} to 10^{-5} per year per galaxy, (Lattimer & Schramm 1976; Narayan, Piran & Shemi 1991; Tutukov & Yungelson 1993; Lipunov, Postnov & Prokhorov 1997; Portegies Zwart & Yungelson 1998; Bethe & Brown 1998; Belczyński & Bulik 1999).

These systems are primary candidates for detection by the gravitational wave detectors such as LIGO (Abramovici et al. 1992). When the binary separation is large, accurate waveforms can be calculated using the post newtonian approximation for point masses (see e.g. Kidder, Will & Wiseman 1992). At small separations,

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a powerful but short burst of waves containing information about the radii and internal structure of the stars is expected. In particular, it may help constrain the equation of state of matter at high densities. At this stage, hydrodynamics will play an important role in the evolution of the system and must be taken into account to make any sense of possible observations.

It is now believed that the gamma ray bursts (GRBs) are of cosmological origin (Meegan et al. 1992; see Fishman & Meegan 1995 for a review), with redshifts to several optical afterglows (Mészáros & Rees 1997) having been measured recently (e.g. Kulkarni et al. 1998, 1999). The extreme energetics of these events and their variability (which arises at the source, Sari & Piran 1997) indicates that the "central engine" must involve a compact object of some sort. The preferred model involves the relativistic expansion of a fireball that produces the gamma rays as a result of internal shocks in the ejecta. Beaming of this fireball would reduce the energy requirements somewhat, and recent observations indicate that this could indeed be the case (Harrison et al. 1999). The nature of the central engine remains unknown at this point. The bimodality in burst durations (Kouveliotou et al. 1995) with classes of long and short bursts (separated at about 2 seconds) hint that there might be two different processes producing the GRBs. Different mechanisms involving neutron stars and/or black holes have been proposed, such as binary coalescence of neutron stars (Paczyński 1986), neutron stars with black holes (Paczyński 1991), catastrophic release of rotational energy through intense magnetic fields (Usov 1992) and failed supernova explosions (Woosley 1993).

We have previously studied the dynamical coalescence of tidally locked black hole–neutron star systems (Lee & Kluźniak 1995; Kluźniak & Lee 1998; Lee & Kluźniak 1999a,b — hereafter Papers I and II) and found that the compressibility of the neutron star affected the process greatly. The outcome of the event was extremely favorable for the production of short gamma ray bursts, with a region of low density along the rotation axis of the binary, and in some cases an accretion disk containing a few tenths of a solar mass around the black hole (Kluźniak & Lee 1998).

We present here our results for the case of irrotational binaries, which are believed to be a more realistic approximation to the conditions encountered in such systems (see below, § 3). We vary the mass ratio $q = M_{NS}/M_{BH}$ and model the neutron star with a stiff equation of state, using $\Gamma = 3$ and $\Gamma = 2.5$.

2. NUMERICAL METHOD

We have used the method known as Smooth Particle Hydrodynamics (SPH) (see Monaghan 1992 for a review). The code is essentially the same one that was used for our previous simulations of black hole–neutron star binaries (Paper I, Paper II) with some minor modifications (Lee 2000, hereafter Paper III). We include the effects of angular momentum losses to gravitational radiation in the quadrupole approximation for point masses, which leads to the orbital decay of the binary.

The neutron star is modeled as a polytrope with a stiff equation of state, so that the pressure is given by $P = K\rho^{\Gamma}$ with Γ and K being constants (see Paper I). We measure mass and distance in units of the mass and radius of the unperturbed (spherical) neutron star (13.4 km and 1.4 $M_{\odot}$ respectively), so that the units of time and density are $\tilde{t} = 1.146 \times 10^{-4}\mathrm{s} \times \left(\frac{R}{13.4\ \mathrm{km}}\right)^{3/2}\left(\frac{M_{\mathrm{NS}}}{1.4\ M_{\odot}}\right)^{-1/2}$ and $\tilde{\rho} = 1.14 \times 10^{18}\mathrm{kg\ m}^{-3} \times \left(\frac{R}{13.4\ \mathrm{km}}\right)^{-3}\left(\frac{M_{\mathrm{NS}}}{1.4\ M_{\odot}}\right)$.

3. INITIAL CONDITIONS

It has been known for some time that realistically, tidal locking is not expected in close binary systems such as the ones treated here, because the viscosity inside neutron stars is not large enough (Bildsten & Cutler 1992; Kochanek 1992). Here we extend our previous work on tidally locked binary systems (Papers I and II) to irrotational systems, which are physically more interesting. In this scenario the *shape* of the star is fixed in the co–rotating frame, but there are internal motions with zero circulation. Each component appears to be counter–spinning with the orbital angular velocity, and in an inertial frame, the star has effectively no spin. A method for constructing approximate solutions was developped by Lai, Rasio & Shapiro (1993), hereafter LRS. They used an energy variational method to find equilibrium solutions for a variety of binary systems assuming a polytropic equation of state and approximating the stars as compressible tri–axial ellipsoids. The black hole–neutron star binaries we treat in this work correspond to irrotational Roche–Riemann binaries (see § 8 in LRS).

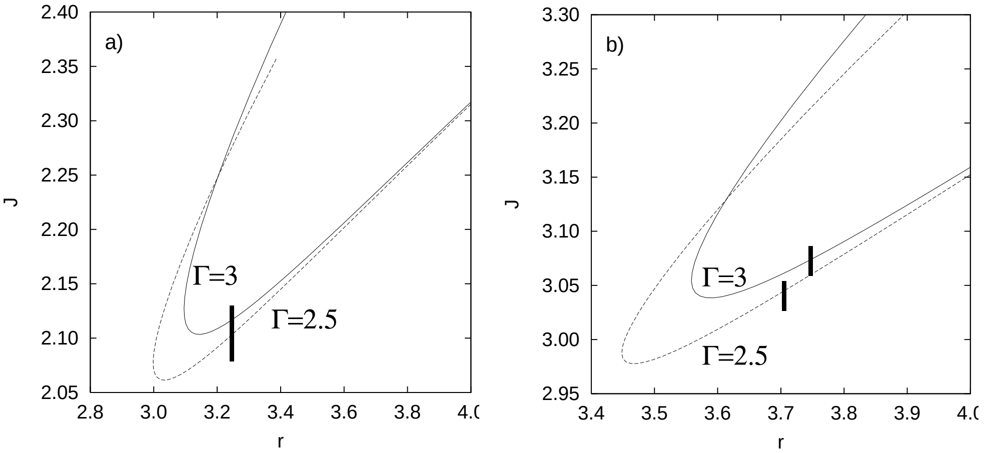

Fig. 1. Total angular momentum as a function of binary separation for irrotational Roche–Riemann binaries as calculated using the method of LRS for $\Gamma = 3$ (solid lines) and $\Gamma = 2.5$ (dashed lines) for (a) $q = 0.5$; (b) $q = 0.31$. The thick vertical lines mark the values of the initial separations used for the dynamical simulations.

We show in Figure 1 the variation in total angular momentum as a function of binary separation for irrotational Roche–Riemann binaries (with various mass ratios and adiabatic indices in the equation of state), as calculated using the method of LRS. The curves exhibit a turning point as the separation is decreased, indicating the presence of an instability in the system. Strictly speaking, the ellipsoidal approximation breaks down close to this turning point, and a full equilibrium solution is necessary (see Uryū & Eriguchi 1999). However, we have chosen the values of the initial separation for our dynamical runs r_i to be slightly *above* the turning point (see Figure 1). The ellipsoidal approximation is then still reasonable, and our equilibrium configurations have not yet reached the point where the neutron star will overflow its Roche lobe. When the dynamical simulation is initiated, the separation will decrease due to the emission of gravitational waves, and mass transfer will start promptly.

4. RESULTS

4.1. *Morphology of the Mergers*

We now briefly describe two dynamical simulations, labeled A50 (with $\Gamma = 3$, initial mass ratio $q = 0.5$ and initial separation $r_i = 3.25$) and B31 (with $\Gamma = 2.5$, $q = 0.31$ and $r_i = 3.70$). The binary separation decreases as a result of angular momentum losses to gravitational radiation, and in every case the neutron star overflows its Roche lobe within one orbital period, initiating mass transfer to the black hole. The neutron star initially becomes elongated, and an accretion stream forms between it and the black hole. This stream winds around the black hole, colliding with itself and producing a thick accretion torus. At the same time as the accretion torus is being formed, a long tidal tail of neutron star matter being ejected through the outer Lagrange point appears. The most striking difference between the two cases is that for $\Gamma = 3$ (run A50) the neutron star core clearly survives this first mass transfer episode as a coherent body, while for $\Gamma = 2.5$ (run B31) the star is almost completely disrupted, although one can discern a bulge in the tidal tail. The core (in the case of run A50) and the bulge (in the case of run B31) make a second perihelion passage around the black hole. In the first case, a second, less pronounced stream forms, feeding the accretion disk, as well as a smaller, secondary tidal tail. In the latter case, the final disruption of the core is not so evident, but one can see that the accretion disk has a complex structure, with two partial rings on one side of the disk. We show in Figure 2 density contours in the orbital plane and in the meridional plane containing the black hole for runs A50 and B31 at the end of the simulation.

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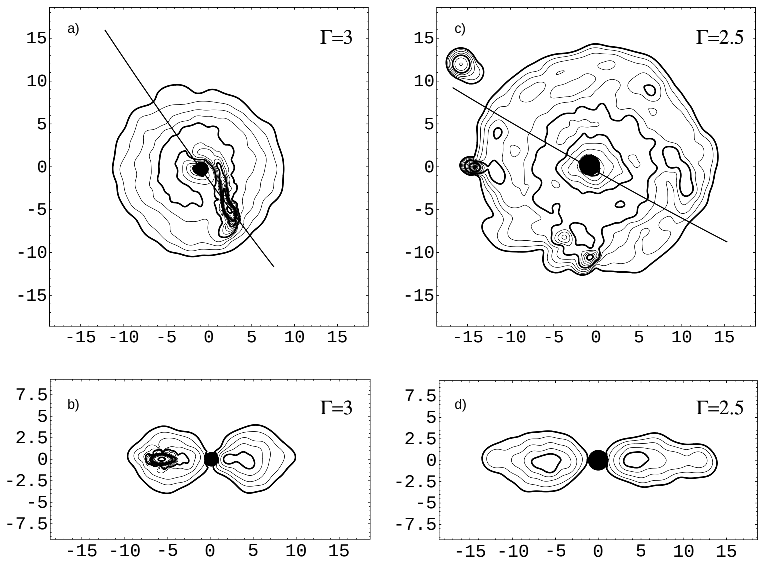

Fig. 2. Density contour plots at $t = t_f$ for runs A50 (a,b) and B31 (c,d) in: (a,c) the orbital plane; (b,d) in the meridional plane shown by the black line in panels (a,c). All contours are logarithmic and equally spaced every 0.25 dex. Bold contours are plotted at $\log \rho = -5, -4, -3, -2, -1$ (if present) in the units defined in section 2.

In all cases with $\Gamma = 3$ the binary is not disrupted, and the surviving core makes successive perihelion passages, transferring some mass to the accretion disk or directly to the black hole each time. For $\Gamma = 2.5$, the neutron star is completely disrupted after (at most) the second perihelion passage, and the accretion disk evolves steadily towards an axisymmetric configuration. In all cases, the primary tidal tail (formed during the first episode of mass transfer) persists as a well–defined large scale structure throughout the simulation. At late times, we see the formation of knots through a sausage instability at approximately regular intervals all along the tail (this has been observed in this kind of simulation before, see e.g. Rasio & Shapiro 1994). Their masses are fairly uniform, of order 2×10^{-3}. This does not occur for soft equations of state (with $\Gamma \leq 2$, see Paper II). The peak accretion rates occur during the initial episode of mass transfer, and are of order 0.05 (equivalent to 0.6 $M_\odot$ ms^{-1}), largely independent of the initial mass ratio and the adiabatic index.

5. DISCUSSION AND CONCLUSIONS

The loss of angular momentum to gravitational wave emission, together with hydrodynamic instabilities, always drives these systems to initiate mass transfer within one orbital period after the start of the dynamical simulations. For $\Gamma = 3$ this episode always leads to the survival of the neutron star core and its transfer to a higher orbit. A long tidal tail of matter stripped from the star appears from the outer Lagrange point, and for high mass ratios ($q = 0.5$ in our simulations) an accretion disk is clearly visible (for lower mass ratios this is not so evident at our current level of resolution). The new binary system is clearly stable, and the slightly elliptical orbit ($0.1 \leq e \leq 0.2$) is small enough to allow secondary mass transfer events to occur at each perihelion passage (two or three more occur during our simulations). Since the mass ratio in the new binary differs substantially from the initial one, and the separation is larger, the timescale for decay of the orbit due to gravitational wave emission is lenghtened considerably, and becomes up to two orders of magnitude greater than the orbital period (calculated for point–mass binaries in the quadrupole approximation). Thus the lifetime of the system may be on the order of tenths of one second. For $\Gamma = 2.5$, the neutron star is eventually completely disrupted and an accretion disc is formed around the black hole, but over a longer timescale (essentially up to and including the second perihelion passage of the core) than in the previous case. A tidal tail of material thrown out from the outer Lagrange point is also formed as described above. These tails survive as well–defined structures throughout the simulations.

The overall morphology of the events is directly reflected in the gravitational radiation waveforms. In the cases where the stellar core survives, the signal continues to exhibit a finite amplitude (albeit greatly reduced) at a frequency corresponding to the new orbital period (approximately 350 Hz vs. 800 Hz at the start of the dynamical simulations). The eccentricity of the orbit produces periodic peaks in the gravitational wave luminosity. This remnant signal is completely absent in the case of $\Gamma = 2.5$, where the waveforms (and luminosity) drop apruptly and practically to zero after the star is disrupted and the accretion disc is formed. The dramatic dependence on the stiffness of the equation of state shows the type of information that could be gleaned from an observation of gravitational waves in the near future, and is similar to what has been found for double neutron star systems by Rasio & Shapiro (RS94), where the persistent emission was due to a lack of axisymmetry in the central object left after the coalescence.

In all cases, the fluid contained in the outer parts of the tidal tails (amounting to 10^{-2}–10^{-1} $M_{\odot}$) appears to be on outbound trajectories (it has enough mechanical energy to escape the gravitational potential well of the black hole–debris torus system). This probably represents an upper bound, since the effects of general relativity are likely to lower this value. We refer the reader to the more detailed analysis performed by Rosswog et al. (1999) and Freiburghaus et al. (1999) where they have used the equation of state of Lattimer & Swesty (1991) and a detailed thermodynamic and nuclear network calculation.

The surviving core (for $\Gamma = 3$) can be driven below the minimum mass required for stability by the successive episodes of mass transfer. If this occurs, an explosion may take place (Page 1982; Blinnikov et al. 1984; Colpi, Shapiro & Teukolsky 1991; Sumiyoshi et al. 1998).

All the accretion discs that form around the black hole during the coalescence are similar in structure, and by the end of our simulations, they are quite close to being azimuthally symmetric. They have masses of a few tenths of a solar mass, with maximum densities and specific internal energies of order 10^{11}g cm^{-3} and 10^{19}erg g^{-1} (or 10 MeV/nucleon) respectively. All of the final configurations have a low degree of baryon contamination along the rotation axis, in the regions directly above and below the black hole. It is low enough so that only modest beaming (of approximately 10°) of a relativistic fireball along this axis would be required in order to avoid being stopped by the fluid in the vicinity of the black hole (Mészáros & Rees 1992). This is encouraging as far as current models of gamma ray bursts (GRBs) are concerned, and confirms our previous results (Lee & Kluźniak 1997; Kluźniak & Lee 1998), where we found that these systems appear to be good candidates for the central engines of short GRBs.

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