Creation of a dense torus in the coalescence of a black hole with a neutron star

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ABSTRACT We used a newtonian SPH (smooth-particle hydrodynamics) code to follow the final stages of evolution of a coalescing binary system of a neutron star and a black hole. We find that the outcome of the “merger” is very sensitive to the equation of state describing the neutron star. A neutron star with a soft equation of state (polytrope with index $\Gamma = 5/3$) is completely disrupted, and a fairly large and long-lived accretion torus is formed.

KEYWORDS: neutron stars – black holes – binaries: evolution – hydrodynamics – gamma-ray bursts

1. INTRODUCTION

The coalescence of a stellar-mass black hole with a neutron star has been discussed as a possible site of the $r$-process and a possible source of gamma-ray bursts (Lattimer & Schramm 1976). It has been expected that in such an encounter, when the loss of angular momentum to gravitational radiation brings the components of the binary sufficiently close, tidal forces will disrupt the neutron star completely (Wheeler 1971). The resulting toroidal structure was supposed to be sufficiently long-lived that its ultimate accretion onto the black hole would proceed on the viscous timescale, thus possibly allowing the appearance of a gamma-ray burst lasting several seconds or minutes (Paczynski 1991, Mészáros and Rees 1993).

2. RESULTS FOR A SOFT E.O.S ($\Gamma = 5/3$)

We have performed two series of SPH runs, with about 17 000 particles each, in which the only essential difference was the polytropic index of the e.o.s. used to model the initial neutron star. The results for $\Gamma = 3$ are as reported previously (Klüniak and Lee 1998). But for $\Gamma = 5/3$, we find that the star is completely disrupted. Here we exhibit representative results obtained for an initial mass ratio of $q = 0.31$. In the calculation, the mass of the neutron star is $M_\star = 1.4M_\odot$ and its (unperturbed) radius $R_\star = 13.4$ km.

The results presented were obtained for an initially tidally locked binary. The initial conditions are obtained by relaxing the polytrope in the presence of the tidal forces.
FIGURE 1. Black hole mass as a function of time.

FIGURE 2. Positions of the SPH particles projected onto the orbital plane at t=2.29 ms. The outline of the black hole is faintly visible, mostly in the first quadrant.
FIGURE 3. Logarithmic density contours in the orbital plane (top panel) and in a meridional plane (bottom panel) at $t=17.2$ ms, after the rapid phase of accretion is over.
field, as described elsewhere (Rasio & Shapiro 1992, Lee & Kluźniak 1995, 1998). For a full description of the code see Lee 1998. Upon relaxing the polytrope we set time equal to zero and allowed the system to evolve dynamically in the presence of a potential mocking up gravitational radiation reaction for two point masses orbiting each other. We have turned off this potential at time \( t = 2.865 \text{ ms} \) when the star was being clearly disrupted; the subsequent computation was purely newtonian. The black hole was modeled as a newtonian point-mass absorbing matter (and momentum) at a spherical boundary of Schwarzschild radius.

In Fig. 2 we show the positions of the SPH particles (projected onto the orbital plane) at time \( t = 2.29 \text{ ms} \) when the black hole is entering a phase of rapid accretion (Fig. 1). Note that \( 1.1 M_\odot \) is accreted in about 15 ms.

Fig. 3 shows the distribution of matter at \( t = 17.2 \text{ ms} \), after the black hole is no longer in the phase of rapid accretion. The lowest contour corresponds to the value of density \( \rho = 10^{-6} M_\odot / R_\ast^3 = 1.14 \times 10^{12} \text{ kg/m}^3 \), distance is in units of the unperturbed stellar radius (\( R_\ast = 13.4 \text{ km} \)). Inspection of the density contours (logarithmically spaced every one-half decade), shows that the star has been completely disrupted and a large accretion torus has formed.

3. DISCUSSION

For the first time in numerical calculations, we have obtained a complete disruption of the star and the persistence of a long-lived toroidal structure as the outcome of the final stages of evolution of a neutron star–black hole binary. Modeling the initial neutron star with a relatively soft e.o.s. was the essential step in obtaining this result in our newtonian simulations. But even in this case, only a small fraction of the mass of the neutron star is locked up in the torus (at \( t = 17.2 \text{ ms} \), \( 0.28 M_\odot \) is within \( 20 R_\ast \) of the black hole).

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