The Final Fate of Coalescing Binary Neutron Stars: Collapse to a Black Hole?

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Abstract. Coalescing compact binaries with neutron star (NS) or black hole (BH) components are important sources of gravitational waves for the laser-interferometer detectors currently under construction, and may also be sources of gamma-ray bursts at cosmological distances. This paper focuses on the final hydrodynamic coalescence and merger of NS–NS binaries, and addresses the question of whether black hole formation is the inevitable final fate of these systems.

1 Introduction

Many theoretical models of gamma-ray bursts (GRBs) rely on coalescing compact binaries (NS–NS or BH–NS) to provide the energy of GRBs at cosmological distances (e.g., Eichler et al. 1989; Narayan, Paczyński, & Piran 1992; Mészáros & Rees 1992). The close spatial association of some GRB afterglows with faint galaxies at high redshifts is not inconsistent with a compact binary origin, in spite of the large recoil velocities acquired by compact binaries at birth (Bloom, Sigursson, & Pols 1999). Currently the most popular models all assume that the coalescence leads to the formation of a rapidly rotating Kerr BH surrounded by a torus of debris. Energy can then be extracted either from the rotation of the BH or from the material in the torus so that, with sufficient beaming, the gamma-ray fluxes observed from even the most distant GRBs can be explained (Mészáros, Rees, & Wijers 1999). However, it is important to understand the hydrodynamic processes taking place during the final coalescence before making assumptions about its outcome. In particular, as will be argued in §3, it is not clear that the coalescence of two $1.4\,M_\odot$ NS will form an object that must collapse to a BH on a dynamical time, and it is not certain either that matter will be ejected during the merger and form an outer torus around the central object.

Coalescing compact binaries are also the most promising sources of gravitational waves for detection by the large laser interferometers currently under construction, such as LIGO (Abramovici et al. 1992) and VIRGO (Bradaschia et al. 1990). In addition to providing a major new confirmation of Einstein's theory of general relativity (GR), including the first direct proof of the existence of black holes (Flanagan & Hughes 1998; Lipunov, Postnov, & Prokhorov 1997), the detection of gravitational waves from coalescing binaries at cosmological distances could provide accurate independent measurements of the Hubble constant and mean density of the Universe (Schutz

1986; Chernoff & Finn 1993; Marković 1993). Expected rates of NS–NS binary coalescence in the Universe, as well as expected event rates in laser interferometers, have now been calculated by many groups. Although there is some disparity between various published results, the estimated rates are generally encouraging (see Kalogera 2000 for a recent review). Many calculations of gravitational wave emission from coalescing binaries have focused on the waveforms emitted during the last few thousand orbits, as the frequency sweeps upward from $\sim 10\,\mathrm{Hz}$ to $\sim 300\,\mathrm{Hz}$. The waveforms in this frequency range, where the sensitivity of ground-based interferometers is highest, can be calculated very accurately by performing high-order post-Newtonian (PN) expansions of the equations of motion for two *point masses* (see, e.g., Owen & Sathyaprakash 1999 and references therein). However, at the end of the inspiral, when the binary separation becomes comparable to the stellar radii (and the frequency is $\gtrsim 1\,\mathrm{kHz}$), hydrodynamics becomes important and the character of the waveforms must change. Special purpose narrow-band detectors that can sweep up frequency in real time will be used to try to catch the last ~ 10 cycles of the gravitational waves during the final coalescence (Meers 1988; Strain & Meers 1991). These "dual recycling" techniques are being tested right now on the German-British interferometer GEO 600 (Danzmann 1998). In this terminal phase of the coalescence, when the two stars merge together into a single object, the waveforms contain information not just about the effects of GR, but also about the interior structure of a NS and the nuclear equation of state (EOS) at high density. Extracting this information from observed waveforms, however, requires detailed theoretical knowledge about all relevant hydrodynamic processes. If the NS merger is followed by the formation of a BH, the corresponding gravitational radiation waveforms will also provide direct information on the dynamics of rotating core collapse and the BH "ringdown" (see, e.g., Flanagan & Hughes 1998).

2 Hydrodynamics of Binary Coalescence

The final hydrodynamic merger of two NS is driven by a combination of relativistic and fluid effects. Even in Newtonian gravity, an innermost stable circular orbit (ISCO) is imposed by *global hydrodynamic instabilities*, which can drive a close binary system to rapid coalescence once the tidal interaction between the two stars becomes sufficiently strong. The existence of these global instabilities for close binary equilibrium configurations containing a compressible fluid, and their particular importance for binary NS systems, were demonstrated for the first time by Rasio & Shapiro (1992, 1994, 1995; hereafter RS1–3) using numerical hydrodynamic calculations. These instabilities can also be studied using analytic methods. The classical analytic work for close binaries containing an incompressible fluid (e.g., Chandrasekhar 1969) was extended to compressible fluids in the work of Lai, Rasio, & Shapiro (1993a,b, 1994a,b,c, hereafter LRS1–5). This analytic study confirmed the existence of dynamical instabilities for sufficiently close binaries. Although these simplified analytic studies can give much physical insight into difficult questions of global fluid instabilities, fully numerical calculations remain essential for establishing the stability limits of close binaries accurately and for following the nonlinear evolution of unstable systems all the way to complete coalescence.

A number of different groups have now performed such calculations, using a variety of numerical methods and focusing on different aspects of the problem. Nakamura and collaborators (see Nakamura & Oohara 1998 and references therein) were the first to perform 3D hydrodynamic calculations of binary NS coalescence, using a traditional Eulerian finite-difference code. Instead, RS used the Lagrangian method SPH (Smoothed Particle Hydrodynamics). They focused on determining the ISCO for initial binary models in strict hydrostatic equilibrium and calculating the emission of gravitational waves from the coalescence of unstable binaries. Many of the results of RS were later independently confirmed by New & Tohline (1997) and Swesty, Wang, & Calder (1999), who used completely different numerical methods but also focused on stability questions, and by Zhuge, Centrella, & McMillan (1994, 1996), who also used SPH. Zhuge et al. (1996) also explored in detail the dependence of the gravitational wave signals on the initial NS spins. Davies et al. (1994) and Ruffert et al. (1996, 1997) have incorporated a treatment of the nuclear physics in their hydrodynamic calculations (done using SPH and PPM codes, respectively), motivated by cosmological models of GRBs. All these calculations were performed in *Newtonian gravity*, with some of the more recent studies adding an approximate treatment of energy and angular momentum dissipation through the gravitational radiation reaction (e.g., Janka et al. 1999; Rosswog et al. 1999), or even a full treatment of PN gravity to lowest order (Ayal et al. 2000; Faber & Rasio 2000).

All recent hydrodynamic calculations agree on the basic qualitative picture that emerges for the final coalescence. As the ISCO is approached, the secular orbital decay driven by gravitational wave emission is dramatically accelerated (see also LRS2, LRS3). The two stars then plunge rapidly toward each other, and merge together into a single object in just a few rotation periods. In the corotating frame of the binary, the relative radial velocity of the two stars always remains very subsonic, so that the evolution is nearly adiabatic. This is in sharp contrast to the case of a head-on collision between two stars on a free-fall, radial orbit, where shock heating is very important for the dynamics (RS1; Shapiro 1998). Here the stars are constantly being held back by a (slowly receding) centrifugal barrier, and the merging, although dynamical, is much more gentle. After typically $1-2$ orbital periods following first contact, the innermost cores of the two stars have merged and the system resembles a single, very elongated ellipsoid. At this point a secondary instability occurs: *mass shedding* sets in rather abruptly. Material (typically $\sim 10\%$ of the total mass) is ejected through the outer Lagrange points of the effective potential and spirals out rapidly. In the final stage, the inner spiral arms widen and merge together, forming a nearly axisymmetric torus around the inner, maximally rotating dense core.

In GR, strong-field gravity between the masses in a binary system is alone sufficient to drive a close circular orbit unstable. In close NS binaries, GR effects combine nonlinearly with Newtonian tidal effects so that the ISCO is encountered at larger binary separation and lower orbital frequency than predicted by Newtonian hydrodynamics alone, or GR alone for two point masses. The combined effects of relativity and hydrodynamics on the stability of close compact binaries have only very recently begun to be studied, using both analytic approximations (basically, PN generalizations of LRS; see, e.g., Lai & Wiseman 1997; Lombardi, Rasio, & Shapiro 1997; Shibata & Taniguchi 1997), as well as numerical calculations in 3D incorporating simplified treatments of relativistic effects (e.g., Baumgarte et al. 1998; Marronetti, Mathews & Wilson 1998; Wang, Swesty, & Calder 1998). Several groups have been working on a fully general relativistic calculation of the final coalescence, combining the techniques of numerical relativity and numerical hydrodynamics in 3D (Baumgarte, Hughes, & Shapiro 1999; Landry & Teukolsky 1999; Seidel 1998; Shibata & Uryu 1999). However this work is still in its infancy, and only very preliminary results of test calculations have been reported so far.

3 Black Hole Formation

The final fate of a NS–NS merger depends crucially on the NS EOS, and on the extraction of angular momentum from the system during the final merger. For a stiff NS EOS, it is by no means certain that the core of the final merged configuration will collapse on a dynamical timescale to form a BH. One reason is that the Kerr parameter J/M^2 of the core may exceed unity for extremely stiff EOS (Baumgarte et al. 1998), although Newtonian and PN hydrodynamic calculations suggest that this is never the case (see, e.g., Faber & Rasio 2000). More importantly, the rapidly rotating core may in fact be dynamically stable. Take the obvious example of a system containing two identical $1.35\,M_\odot$ NS. The total baryonic mass of the system for a stiff NS EOS is then about $3\,M_\odot$. Almost independent of the spins of the NS, all hydrodynamic calculations suggest that about 10% of this mass will be ejected into the outer torus, leaving at the center a *maximally rotating* object with baryonic mass $\simeq 2.7\,M_\odot$ (Any hydrodynamic merger process that leads to mass shedding will produce a maximally rotating object since the system will have ejected just enough mass and angular momentum to reach its new, stable quasi-equilibrium state). Most stiff NS EOS (including the recent "AU" and "UU" EOS of Wiringa et al. 1988) allow stable, maximally rotating NS with baryonic masses exceeding $3\,M_\odot$ (Cook, Shapiro, & Teukolsky 1994), i.e., well above the mass of the final merger core. Differential rotation (not taken into account in the calculations of Cook et al. 1994) can further increase this maximum stable mass very significantly (see Baumgarte, Shapiro, & Shibata 2000). However, for slowly rotating stars, the same EOS give maximum stable baryonic masses in the range $2.5 - 3\,M_{\odot}$. Thus the final fate of the merger depends critically on its rotational profile and total angular momentum.

Note that other processes, such as electromagnetic radiation, neutrino emission, and the development of various secular instabilities (e.g., r-modes), which may also lead to angular momentum losses, take place on timescales much longer than the dynamical timescale (see, e.g., Baumgarte & Shapiro 1998, who show that neutrino emission is probably negligible). These processes are therefore decoupled from the hydrodynamics of the coalescence. Unfortunately their study is plagued by many fundamental uncertainties in the microphysics.

The question of the final fate of the merger also depends crucially on the evolution of the fluid vorticity during the final coalescence. Close NS binaries are likely to be *nonsynchronized*. Indeed, the tidal synchronization time is almost certainly much longer than the orbital decay time (Kochanek 1992; Bildsten & Cutler 1992). For NS binaries that are far from synchronized, the final coalescence involves some new, complex hydrodynamic processes (Rasio & Shapiro 1999). Consider for example the case of an irrotational system (containing two nonspinning stars at large separation; see LRS3). Because the two stars appear to be counter-spinning in the corotating frame of the binary, a *vortex sheet* (where the tangential velocity jumps discontinuously by $\Delta v \sim 0.1\,c$) appears when the stellar surfaces come into contact. Such a vortex sheet is Kelvin-Helmholtz unstable on all wavelengths and the hydrodynamics is therefore extremely difficult to model accurately given the limited spatial resolution of 3D calculations. The breaking of the vortex sheet generates some turbulent viscosity so that the final configuration may no longer be irrotational. In numerical simulations, however, vorticity is quickly generated through spurious shear viscosity, and the merger remnant is observed to evolve rapidly (in just a few rotation periods) toward uniform rotation.

The final fate of the merger will be affected drastically by these processes. In particular, the shear flow inside the merging stars (which supports a highly triaxial shape; see Rasio & Shapiro 1999) may in reality persist long enough to allow a large fraction of the total angular momentum in the system to be radiated away in gravitational waves. In this case the final merged core may resemble a Dedekind ellipsoid, i.e., it will have a triaxial shape supported entirely by internal fluid motions, but with a stationary shape in the inertial frame (so that it no longer radiates gravitational waves). This state will be reached on the gravitational radiation reaction timescale, which is no more than a few tens of rotation periods. On the (possibly much longer) *viscous timescale*, the core will then evolve to a uniform, slowly rotating state and will likely collapse to a BH. In contrast, in all 3D numerical simulations performed to date, the shear is quickly dissipated, so that gravitational radiation never gets a chance to extract more than a small fraction ($\sim 10\%$) of the angular momentum, and the final core appears to be a uniform, maximally rotating object exactly as in calculations starting from synchronized binaries. However this behavior is most likely an artefact of the large spurious shear viscosity present in the 3D simulations.

In addition to their obvious significance for gravitational wave emission, these issues are also of great importance for models of GRBs that depend on energy extraction from a torus of material around the central BH. Indeed, if a large fraction of the total angular momentum is removed by the gravitational waves, rotationally-induced mass shedding may not occur at all during the merger, leaving a BH with no surrounding matter and no way of extracting energy from the system.

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