

# The swallowing of a quark star by a black hole

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## ABSTRACT

In three-dimensional smooth particle hydrodynamic simulations of the coalescence of a quark star with a pseudo-Newtonian black hole all of the quark matter is quickly accreted by the black hole. The Madsen–Caldwell–Friedman argument against the existence of quark stars may need to be re-examined.

**Key words:** dense matter – gravitational waves – hydrodynamics – binaries: close – stars: general – gamma-rays: bursts.

## 1 INTRODUCTION

An astrophysical argument has been invoked against the existence of quark stars in our Galaxy: in the coalescence of a quark star with a comparably compact object a huge number of small fragments of quark matter is expected to be ejected from the binary and to pollute the galactic environment (Madsen 1988; Caldwell & Friedman 1991) precluding formation of glitching neutron stars (Alpar 1987). We have set out to test this expectation against actual simulations of the coalescence process.

In a first attempt to model quark stars in smooth particle hydrodynamics (SPH), we have already carried out strictly Newtonian simulations of the black hole coalescence of stars modelled with an equation of state (e.o.s.) appropriate to self-bound quark matter (Lee, Kluźniak & Nix 2001, henceforth Paper I) and compared the outcome against previously published results (Lee & Kluźniak 1999a,b; Kluźniak & Lee 1998; Lee 2000, 2001) of analogous simulations of the coalescence of a black hole and a polytrope, taken to represent a neutron star. We have found significant differences between the two sets of simulations. Although the star was disrupted, to a degree, and a disc of matter formed around the black hole in each of the two cases, for the quark star system we have found no clear evidence of mass ejection in those Newtonian simulations, to the limit of our resolution.

Here, we report the results of three-dimensional hydrodynamic simulations of the coalescence of a quark star moving in a pseudo-potential (e.g. Paczyński & Wiita 1980) modelling salient features of general relativistic motion around black holes. The coalescence is over much more quickly than in the Newtonian case. The black hole swallows the quark star in one gulp.

## 2 QUARK STARS

If quark matter is stable at zero pressure, quark stars should exist, and models of such stars, i.e. of a massive amount of quark fluid in

hydrostatic equilibrium, have been constructed in general relativity (Itoh 1970; Bodmer 1971; Brecher & Caporaso 1976; Witten 1984; Haensel, Zdunik & Schaeffer 1986; Alcock, Fahri & Olinto 1986a). The properties of rapidly rotating quark stars of all masses have also been investigated in general relativity (Gourgoulhon et al. 1999; Stergioulas, Kluźniak & Bulik 1999; Zdunik et al. 2000; Gondek-Rosińska et al. 2001; Amsterdamski et al. 2002).

Population studies indicate that if quark stars exist at all, their number may be comparable to the number of black holes, and a significant number of compact binaries with a quark star member is expected (Belczyński, Bulik & Kluźniak 2002).

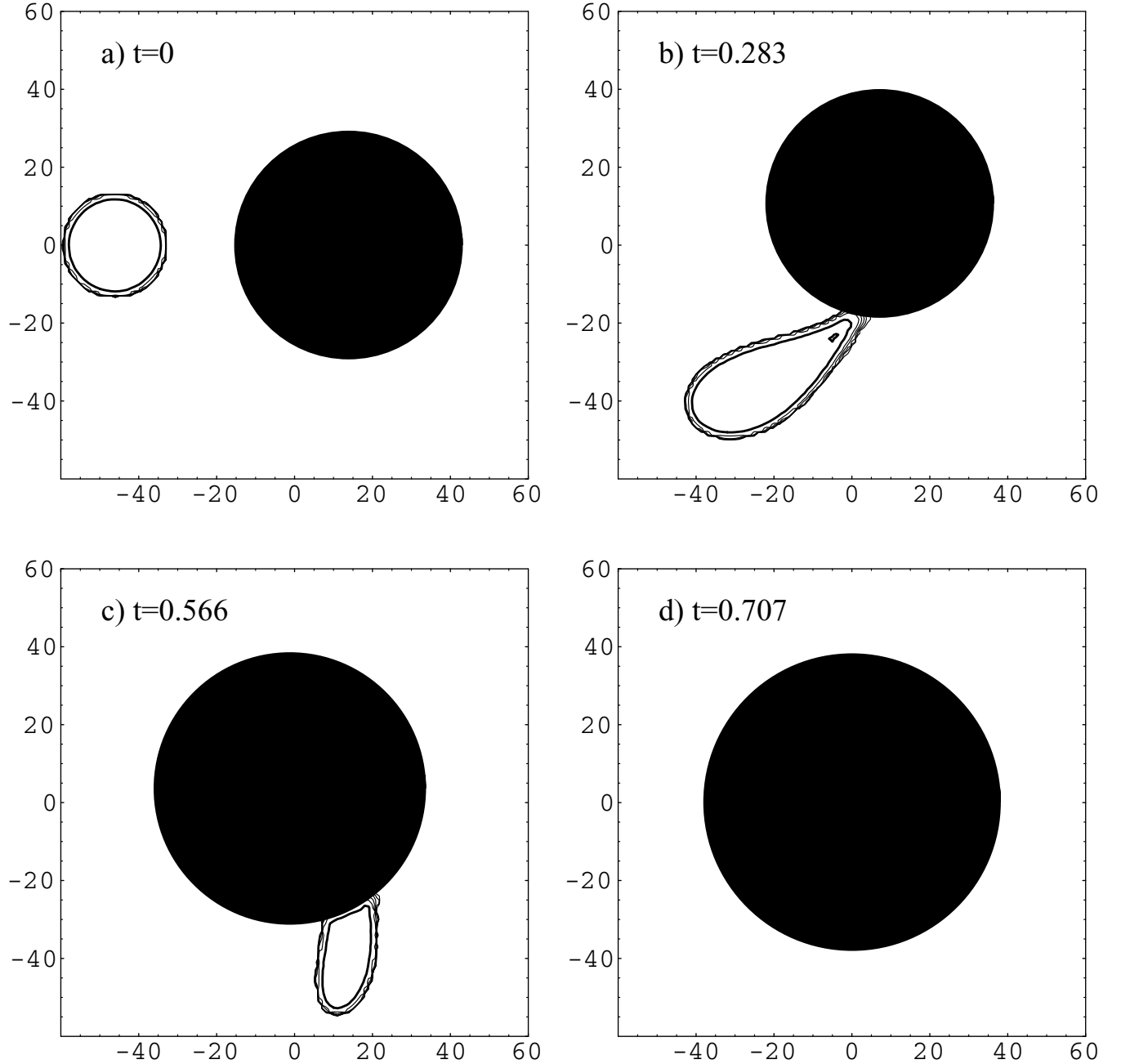
Coalescing compact objects are prime candidates for detection with ground-based gravitational wave detectors. Processes involving quark stars have been invoked to explain a number of other high-energy phenomena, as well, from soft gamma repeaters to properties of radio pulsars (e.g. Alcock, Fahri & Olinto 1986b; Horvath, Vucetich & Benvenuto 1993; Zhang, Xu & Qiao 2000; Usov 2001; Cheng & Dai 2002). Quark stars are especially attractive as a theoretical candidate for a gamma-ray burst (GRB) source – models involving quark stars would neatly sidestep the difficult problem of baryon contamination, as there are no baryons in quark matter (Paczynski 1991). However, if ejection of quark matter seeds does occur in binary coalescence of quark stars, GRB models involving such a process (Haensel, Paczyński & Amsterdamski 1991) would be difficult to reconcile with the presence of young neutron stars in our Galaxy (Kluźniak 1994).

A more complete discussion of the issues touched upon here can be found in Paper I, and in the reviews by Cheng, Dai & Lu (1998) and Madsen (1999).

## 3 THE SIMULATION

Quark matter can be described by a linear equation of state (e.g. Zdunik 2000). In the MIT-bag model, in the limit of massless quarks, the pressure is  $P = c^2(\rho - \rho_0)/3$  (Fahri & Jaffe 1984), with  $\rho c^2$  the energy density. We take  $2.634 \times 10^{14} \text{ g cm}^{-3} < \rho_0 < 7.318 \times 10^{14} \text{ g}$

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**Figure 1.** Density contours in the orbital plane during the dynamical simulation of the black hole–strange star binary with initial mass ratio  $q = 0.3$  and  $M_{\text{SS}} = 2 M_{\odot}$  (run B30). The orbital rotation is counterclockwise. All contours are logarithmic and equally spaced every 0.25 dex, with a bold contour at  $\rho = \rho_0$ . In fact, the presence of the thin contours is largely a numerical artefact (Section 3). The time for each frame is given in milliseconds, and the axes are labelled in km.

$\text{cm}^{-3}$  in the various runs reported here. We numerically construct a non-rotating Newtonian star with this e.o.s., and place it in binary orbit around a black hole, modelled as a spherical vacuum cleaner with a pseudo-Newtonian potential (Lee & Kluźniak 1995, 1999b).

The initial separation was chosen to allow a quick merger. The spiral-in is at first caused by loss of angular momentum to gravitational radiation. We have found the results to be insensitive to the initial separation and to the choice of pseudo-potential (see below), as well as to the placement of the absorbing boundary around the ‘black hole.’ The low shear viscosity of quark matter suggests that, just as is the case for neutron stars (Bildsten & Cutler 1992),

a quark star in a coalescing binary will not be tidally locked. We further assume that the star has not been born a millisecond rotator. This is why we decided on a non-rotating quark star in the initial conditions.

We neglect the very thin crust which may be present in quark stars (Alcock et al. 1986a). The star should have a sharp boundary at zero pressure, and density  $\rho_0$  (the bold contour in Fig. 1). Although the density of self-bound quark fluid cannot drop below  $\rho_0$ , in presenting the results we draw also five contours of average spatial density of values successively lower by factors of 1.78. This allowed us to trace the distribution of quark droplets in the Newtonian simulation

**Table 1.** Basic parameters for selected runs. The table lists, for each run, the radius and mass of the star, the initial mass ratio  $q = M_{\text{SS}}/M_{\text{BH}}$ , the initial orbital separation, the density of quark matter at zero pressure  $\rho_0$ , the time at which gravitational radiation reaction was switched off, the time at which the simulation finished, and the initial number of particles.

Run	$R_{\text{SS}}$ (km)	$M_{\text{SS}}/M_{\odot}$	$q$	$r_i/R_{\text{SS}}$	$\rho_0/10^{14} \text{ g cm}^{-3}$	$t_{\text{rad}}/10^{-4} \text{ s}$	$t_f/10^{-4} \text{ s}$	$N$
A50	9.0	1.5	0.50	3.5	7.318	2.276	4.049	17 256
A30	9.0	1.5	0.30	5.0	7.318	3.457	5.311	17 256
B50	12.0	2.0	0.50	3.5	4.116	3.038	5.407	17 256
B30	12.0	2.0	0.30	5.0	4.116	4.613	7.088	17 256
C50	15.0	2.5	0.50	3.5	2.634	3.800	6.755	17 256
C30	15.0	2.5	0.30	5.0	2.634	5.770	8.863	17 256

(Paper I). In the current simulation we detect no low density regions (thin contours in Fig. 1), other than the contours just outside the star – these are a numerical artefact reflecting the size of the SPH kernel (close to 800 m at the stellar boundary) over which the spatial average is performed.

#### 4 PSEUDO-NEWTONIAN BLACK HOLE

Paczynski & Wiita (1980) modelled relativistic accretion discs using Newtonian equations of motion in a pseudo-potential given by

$$\Phi_{\text{PW}}(r) = -\frac{GM_{\text{BH}}}{r - r_g}, \quad (1)$$

where  $r_g = 2GM_{\text{BH}}/c^2$ . This function does not satisfy the Laplace equation, but is spherically symmetric, and quite useful in reproducing such features of orbital motion around a Schwarzschild black hole as the innermost stable orbit, and hence of modelling relativistic accretion flows. In our simulations, we take this potential to describe the gravity of the black hole. We place an absorbing boundary at  $r = 3GM_{\text{BH}}/c^2$ , corresponding to the radius of the photon orbit in Schwarzschild geometry. The black discs in Fig. 1 have this radius. When an SPH particle touches the boundary, it is removed from the simulation and its mass and momentum are added to the black hole. The code conserves angular momentum. In other runs, not reported in Table 1, we have placed the absorbing boundary at various other radii in the range  $(2.1r_g, 4r_g)$ . There was no change of the results.

The Paczynski–Wiita pseudo-potential is divergent at  $r_g$ , i.e. it is very attractive close to that radius. To test whether this was the source of the rapid accretion of the quark star by the black hole, we have also used another pseudo-potential devised by us to reproduce the Schwarzschild ratio of the orbital and epicyclic frequencies

$$\Phi_{\text{KL}}(r) = -\frac{GM_{\text{BH}}}{3r_g} \left(1 - e^{3r_g/r}\right). \quad (2)$$

It was not.

#### 5 NUMERICAL METHOD

We have used smooth particle hydrodynamics for the calculations presented here (see Monaghan 1992). The code is the same as that used for our previous calculations of strange star–black hole coalescence using Newtonian physics (Paper I), the only difference being in the computation of the gravitational potential produced by the black hole and of the gravitational radiation reaction terms. For the runs reported here, we use the pseudo-potential of equation (1). Our treatment of gravitational radiation reaction is similar to that employed previously (Lee & Kluźniak 1999b), except that we now use the orbital frequency in the Paczynski–Wiita potential,  $\Omega = [\sqrt{G(M_{\text{BH}} + M_{\text{SS}})/r}]/(r - r_g)$ , which is larger than

the Schwarzschild value. Following Landau & Lifshitz (1975), we take

$$\frac{dE_{\text{orb}}}{dt} = -\frac{32G\mu^2\Omega^6 r^4}{5c^5}, \quad (3)$$

with  $\mu = M_{\text{SS}}M_{\text{BH}}/(M_{\text{SS}} + M_{\text{BH}})$  and  $r$  the binary separation. The coalescence now proceeds much faster than in the Newtonian runs of Paper I, and the star is accreted within one orbital period from the start of the simulation (in less than one millisecond).

The strange star is constructed using the MIT e.o.s. for massless quarks, as outlined in Paper I. Indeed, we use the same initial stars as for the runs shown there. The data for our present dynamical runs is summarized in Table 1.

#### 6 RESULTS

In the pseudo-potentials used for the current simulation, as in general relativity, the pull of gravity is so strong that the centrifugal barrier has only finite height, and vanishes entirely for angular momenta lower than that in the marginally stable orbit. As a result, the strange star is accreted whole by the black hole. This happened for all the runs we performed, regardless of the initial mass ratio, binary separation, stellar mass and radius, placement of the black hole boundary, or the form of the pseudo-Newtonian potential used. No fragment of quark matter survives the encounter to form an accretion disc around the black hole (let alone be ejected from the system). The computed gravitational wave signal accordingly vanishes abruptly once the star is accreted.

The results strongly suggest that in the binary coalescence of a quark star and a black hole no matter is lost from the system at all. No comparable simulations have as yet been reported for two quark stars in a binary, nor any relativistic simulation of any coalescence process involving a quark star. It may be assumed that the current results are the best guide to the state of affairs: no quark nuggets are ejected in the binary coalescence. At present, the existence of quark stars in our Galaxy cannot be ruled out.

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