EXPLOSIONS OF NEUTRON STAR FRAGMENTS EJECTED DURING BINARY COALESCENCE

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ABSTRACT. Small, self-gravitating fragments of unstable neutronized matter may be produced during the final coalescence of neutron star binaries. An energy $\sim 10^{50}$ erg is expected to be released in a burst of antineutrinos and high-energy photons.

1. Introduction

It is well known that there exists a *minimum mass* $M_{\min}$ for a neutron star, below which no stable hydrostatic equilibrium can exist. At $M_{\min}$, an instability to expansion is expected to be triggered by β-decays and nuclear fissions. Colpi, Shapiro, & Teukolsky (1989, 1991) have calculated the evolution of such an unstable neutron star. They showed that the star disrupts catastrophically, on a time scale of a few milliseconds to a few seconds. These calculations were carried out using realistic microphysics but an approximate dynamical model based on homogeneous Newtonian spheroids. In the first part of this paper, we summarize the results of a more recent, improved treatment (Colpi et al. 1993, hereafter CST).

The astrophysical relevance of this process has been discussed by various authors (Clark & Eardley 1977; Blinnikov et al. 1984, 1990) in the context of neutron star binaries. Early studies of the terminal evolution of these systems suggested the possibility of stable mass transfer from the lighter component to the heavier. This could result in mass stripping of the lighter neutron star down to the minimum mass. More recent investigations, however, indicate that stable mass transfer is very unlikely, except perhaps in rather special and unrealistic cases, e.g., when the mass ratio is far from unity (Bildsten & Cutler 1992; Kochanek 1992; Lai, Rasio & Shapiro 1994). In general, tidal disruption of the lighter star and coalescence of the system will occur on a dynamical time scale. In the second part of this paper, we propose a new scenario for the explosion of neutronized matter following the dynamical coalescence of two neutron stars. We discuss the possible relevance of this scenario to cosmological models of γ-ray bursters (see, e.g., Narayan, Paczyński, & Piran 1992).

2. Exploding Neutron Stars Below the Minimum Mass

CST follow the evolution of an unstable neutron star below $M_{\min}$ using a Lagrangian hydrodynamical code that accounts for the inhomogeneous structure of the star. The seeds of the instability are the β-decaying nuclei in the crust layers. It is thus important to consider how the instability rises and spreads: Does the unstable star explode suddenly when β-decays are well under way, or does it evaporate on the β-decay time scale by slowly ejecting material from the surface? In the expansion, does a bound lower mass remnant form? To address these questions one must incorporate into the dynamical calculation a *nonequilibrium* equation of state. CST adopt the Harrison-Wheeler nuclear model, giving $M_{\min} = 0.196 M_{\odot}$. Matter consists of free electrons, dripped neutrons, and heavy nuclei unstable to β-decay. During the decompression, nuclei follow a path similar to the r-process, terminating with fission. The neutron star is initially in hydrostatic equilibrium. It is perturbed out of β-equilibrium by slowly stripping mass from its surface. The expansion is then driven by the ensuing β-decays and nuclear fissions. Stability is lost at a lower critical mass, $M_{\rm crit} = 0.8 M_{\rm min}$, as matter follows the nonequilibrium equation of state during the perturbation.

The evolution is found to proceed along three distinct phases: (1) In the first phase the outermost layers reach quickly the escape velocity, the outflow properties depending sensitively on the way mass stripping is numerically handled. (2) A second phase of *secular* expansion follows that involves the intermediate layers of the crust where the seeds of the instability are present. This phase, similar to an *evaporation* process, lasts $\sim 10^2$–10^5 s, the spread corresponding to uncertainties in the β-decay timescale and in the stripping process. (3) Following the loss of the crust layers, a phase of sudden *explosion* sets in: the inner layers accelerate abruptly, attaining escape velocity in a few milliseconds. During core explosion, nuclear transformations change the composition of matter so that it becomes progressively richer in heavy nuclei unstable to fission. The energy per baryon ϵ_B deposited by fission is ~ 0.5–1 MeV. A fission "wave" forms in the overlying intermediate layers that propagates inwards, heating the whole star up to a temperature $\sim 10^{10}$ K. Figure 1 illustrates the evolution during this explosive phase. The ejected debris move at a mean velocity $\sim 5\times10^4\,{\rm km\,s^{-1}}$, corresponding to a total kinetic energy output $\sim 5\times10^{49}$ erg. An antineutrino burst with peak luminosity $L_{\bar\nu} \sim 10^{50}$–$10^{52}\,{\rm erg\,s^{-1}}$ signals the onset of the explosion.

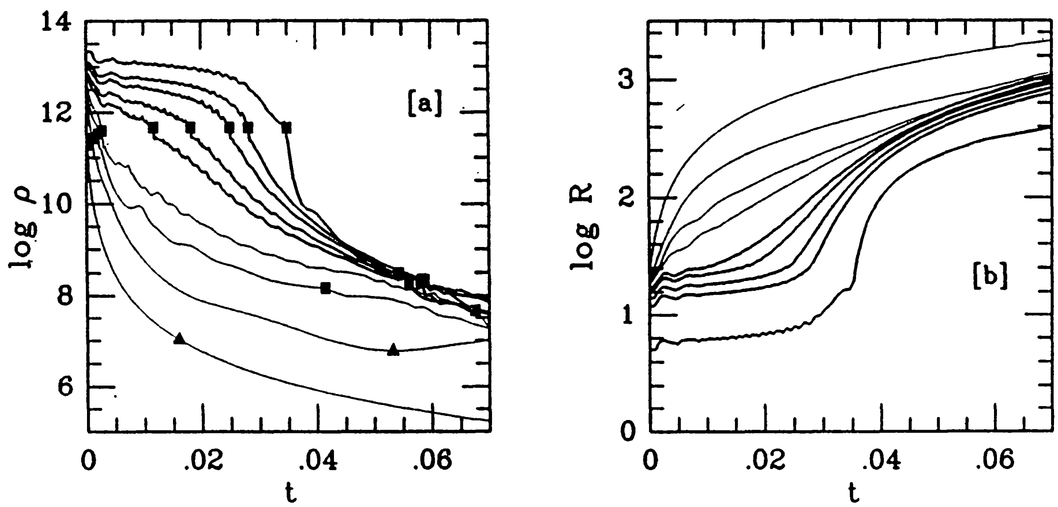

Figure 1. Density ρ in ${\rm g\,cm^{-3}}$ [a], and radius R in km [b] as a function of time (in sec) for $M = M_{\rm crit}$. Solid (heavy) lines denote crust (core) shells. Squares indicate the occurrence of fission; triangles, the reabsorption of dripped neutrons.

3. Explosions of Fragments Ejected During Binary Coalescence

3.1 Hydrodynamics of Neutron Star Binary Coalescence

The hydrodynamics of coalescing neutron star binaries has been studied recently by Rasio & Shapiro (1992, 1994; see also Rasio, this volume) using the smoothed particle hydrodynamics (SPH) method. When the separation between the two stars becomes smaller than a critical value $r_{dyn} \simeq 3R$, where R is the stellar radius, the system becomes *dynamically unstable* to small radial perturbations of the orbital motion (Lai et al. 1993, 1994). For neutron stars with a stiff equation of state (adiabatic exponent $\Gamma \gtrsim 2$), the onset of instability corresponds to a binary configuration that is still slightly *detached*. The instability leads to the coalescence and merging of the two stars on a time scale comparable to the orbital period. For two identical neutron stars of mass $M = 1.4\,M_\odot$ and radius $R \simeq 10$ km, the binary separation at the onset of instability is $r_{dyn} \simeq 30$ km and the corresponding orbital period is $P_{orb} \approx 1.5$ ms. The complete dynamical coalescence and merging of the two stars into a single massive object then takes about 7 ms.

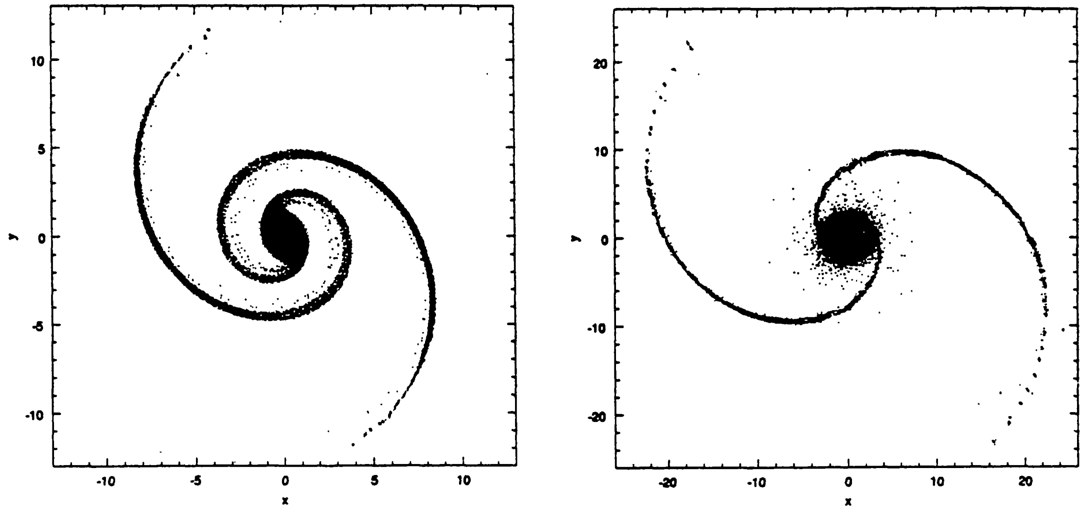

Figure 2. Rotational instabilities and mass shedding through spiral arms develop during the dynamical coalescence of two neutron stars. In this SPH calculation, two identical stars modeled as polytropes with $\Gamma = 3$ were placed initially in an equilibrium binary configuration on the verge of dynamical instability. Projections of all SPH particles into the orbital plane are shown at two different times. The units are such that $G = M = R = 1$, where M and R are the mass and radius of a neutron star. The orbital rotation is counterclockwise.

During the dynamical evolution, about 20% of the total mass is ejected from the central object through the outer Lagrangian points of the effective potential and spirals out rapidly (Fig. 2). The spiral arms, although transient in nature, form a very extended coherent structure that can subsist for a large number of internal dynamical times. Unfortunately, the spatial (and mass) resolution of the numerical simulations is not sufficient to determine accurately the internal structure and dynamical evolution of the spiral arms. Fragmentation is expected since they are strongly self-gravitating. This may indeed be visible in the outer parts of the spiral arms at late times in the simulations (see Fig. 2b), but both the size of the fragments and the thickness of the arms elsewhere are at the limit of the spatial resolution. Therefore, we now turn instead to a simple qualitative analysis of the dynamical evolution of the ejected material.

3.2 Qualitative Analysis of Spiral Arm Fragmentation

Self-gravitating fluid jets and cylinders are subject to "sausage" instabilities (also called "varicose" instabilities, cf. Chandrasekhar 1961). These instabilities lead to fragmentation into self-gravitating lumps of fluid, with the typical diameter of each lump comparable to the wavelength of the fastest growing mode, $\lambda_f = 2\pi R/0.580$, where R is the radius of the cross-section. Since both the total length and the typical curvature radius of a spiral arm are much larger than the arm's diameter, we can treat the arms approximately as long, thin cylinders of fluid.

The numerical simulations indicate that about 20% of the total mass is ejected into the spiral arms. Each arm may then contain a mass $M_a \sim 0.3 M_\odot$. The typical radius of the arm's cross-section is $R_a \simeq 2$–$3\,\mathrm{km}$, while its total length is $L_a \sim 200$–$300\,\mathrm{km}$. The typical mean density in the arms is therefore $\rho_a \sim 10^{14}\,\mathrm{g\,cm^{-3}}$. We can now estimate the typical number of fragments that should form. The most unstable wavelength is $\lambda_f \sim 20\,\mathrm{km}$, so each arm should fragment into $N_f \sim L_a/\lambda_f \sim 10$ lumps, each containing a mass $M_f \sim 0.03 M_\odot$. The tidal field of the central object, of mass $M_c \simeq 2.2\,M_\odot$, becomes important within $r_{tidal} \simeq R_a (M_c/M_f)^{1/3} \sim 10\,\mathrm{km}$. Most of the fragments form well outside of this distance and should therefore be strongly self-gravitating.

The characteristic time for break-up is $\tau_f \simeq 4 \times (4\pi G\rho_a)^{-1/2} \sim 1\,\mathrm{ms}$ (Chandrasekhar 1961). This is shorter than the β-decay time scale $\tau_\beta \simeq 20\Delta^{-4}\mu_{e,100}^{-2}\,\mathrm{ms}$, where Δ in MeV measures the deviation of matter from β-equilibrium and $\mu_{e,100}$ is the electron chemical potential in units of 100 MeV. Thus matter in the spiral arms fragments *before* becoming unstable to β-decay. The resulting self-gravitating lumps have masses $\ll M_{\min}$ and are therefore highly unstable. Explosions should occur, similar to the one calculated in §2. We estimate below the energy release, following Colpi et al. (1989, 1993).

3.3 Relevance to Gamma-Ray Bursts

Each unstable fragment of mass $M_f \sim 0.03 M_\odot$ should release $\sim 10^{49}\,\mathrm{erg}$ in antineutrinos with mean $\bar{\nu}$-energy ~ 5 MeV. At the onset of explosion, the luminosity $L_{\bar{\nu}} \sim N_f \times 10^{50} - -10^{52}\,\mathrm{erg\,s^{-1}}$. The thermal energy content resulting from β-decays and fissions in each fragment is $\simeq \epsilon_B\,(M_f/m_B) \sim 10^{49}\,\mathrm{erg}$ and is available for photon emission. The estimate of the photon energy release is, however, quite uncertain. If the length scale of temperature gradients at the surface of each expanding fragment is comparable to the photon mean free path, the photon luminosity can be as large as $L_{ph} \sim 2\pi R_a \lambda_f\, \sigma T^4 \sim 10^{48}\,\mathrm{erg\,s^{-1}}$ for $T = 10^{10}$ K. X-rays and γ-rays would be produced with total luminosity $N_f L_{ph} \sim 10^{49}\,\mathrm{erg\,s^{-1}}$. Photon absorption could reduce this estimate by several orders of magnitude, however (Colpi et al. 1991). The kinetic energy of the exploding debris, $E_k \sim 10^{49}\,\mathrm{erg}$ is not large enough for the material to climb out the gravitational potential of the central merger.

The time structure of the antineutrino and photon bursts depends on two relevant time scales: the fragmentation time $\tau_f \sim 1\,\mathrm{ms}$ (which is also roughly equal to the typical time for a fragment to cross the line of sight), and the explosion time, comparable to τ_β. This time can vary between a millisecond and a few seconds, depending on the type of initial evolution out of β-equilibrium. The detailed hydrodynamics of the break-up process will determine the exact distribution of explosion times, as well as the total duration of the burst.

Conclusions

If they are cosmological in origin, γ-ray bursts require a photon energy release $\sim 10^{51}\,\mathrm{erg}$. This simple energy requirement is probably *not* satisfied by the mechanism discussed above. Under rather optimistic assumptions, we estimate that the exploding fragments carry out at most a total energy $\sim 10^{50}\,\mathrm{erg}$. Nevertheless, if γ-ray bursts are indeed produced by coalescing neutron star binaries, the emission from these exploding fragments may contribute to the total luminosity and affect the spread and shape of the burst profile.

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