THE ASTROPHYSICAL JOURNAL, 375:209–215, 1991 July 1

GAMMA-RAY BURSTS FROM COLLIDING STRANGE STARS

P. HAENSEL,[1,2] B. PACZYŃSKI,[1] AND P. AMSTERDAMSKI[2]
Received 1990 November 26; accepted 1991 January 2

ABSTRACT

The rate of collisions between the neutron stars is $\sim 10^{-4}$ yr^{-1} in our Galaxy and $\sim 10^5$ yr^{-1} within the Hubble distance. The collisions are the final phases of binary orbit decay driven by gravitational radiation and may produce gamma-ray bursts detectable at extragalactic distances. If strange stars exist then their collisions must release $\sim 10^{50}$ ergs in gamma rays over ~ 0.2 s. Such events should be detectable out to ~ 1 Gpc with the current instruments.

The distance to the majority of gamma-ray bursts is not known at this time. The Burst and Transient Source Experiment (BATSE) on Gamma Ray Observatory should determine the distance scale by determining the angular distribution of very weak bursts. If the majority of gamma-ray bursts turn out to be extragalactic, and if their distances are ~ 1 Gpc, then the collisions between strange stars may be the least speculative events that might account for so energetic bursts.

Subject headings: gamma-rays: bursts — relativity — stars: neutron

1. INTRODUCTION

Mergers of two neutron star members of a close binary should be fairly common events, with the rate estimated at 10^{-4} yr^{-1} in our Galaxy (Clark, van den Heuvel, & Sutantyo 1979). A merger follows a binary orbit decay driven by gravitational radiation. There are already three pairs of neutron stars known, with periods between 8 and 10 hr, that will merge within the next 10^8–10^9 yr: PSR 1913+16 (Taylor & Weisberg 1989 and references therein), PSR 2127+11C in M15c (Anderson et al. 1990), and PSR 1534+12 (Wolszczan 1990).

A large variety of consequences of mergers and/or collisions between two neutron stars were discussed in the literature.

Short-period binaries made of two neutron stars evolve because of gravitational radiation losses (Dyson 1963; Clark & Eardley 1977; Clark 1979; Ostriker 1979; Gilden & Shapiro 1984; Quinlan & Shapiro 1989; Taylor & Weisberg 1989, Colpi, Shapiro, & Teukolsky 1991, and references therein). While the two components merge they radiate a strong pulse of gravitational radiation. Such events may be detectable out the Virgo cluster of galaxies with the currently planned generation of gravitational wave detectors (Thorne 1987 and references therein).

Neutron star mergers and collisions, as well as mergers between the neutron stars and black holes, can also be the site for exotic nucleosynthesis (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Symbalisty & Schramm 1982; Meyer 1989 and references therein).

When the merged neutron star is formed, it is likely to be rapidly and differentially rotating. Such an object may eject a jet of matter along its rotation axis, pretty much like a single rotating neutron star may do when it has just formed in a dynamical collapse (LeBlanc & Wilson 1970; Schramm & Barkat 1972; Meier et al. 1976; Symbalisty 1984).

There are many unresolved issues. For example: how long can a merged neutron star survive before collapsing into a black hole? How much mass may be ejected as a wind, as a jet, or in another bulk form? How much X-ray and/or gamma-ray emission is to be expected?

These events are not hypothetical, and the rate of $\sim 10^{-4}$ yr^{-1} in our Galaxy is unlikely to be wrong by more than one order of magnitude. Therefore, there must be $\sim 10^5$ neutron star mergers per year within the Hubble distance. Neutron star mergers are interesting as sources of kiloHertz gravitational radiation, and as possible sites of exotic nucleosynthesis. They may be even more interesting as events that could be directly observable in some part of electromagnetic spectrum.

The final stages of the binary decay are so rapid that the merger is really a collision (Paczyński 1990b, 1991). The merger/collision of two neutron stars releases about as much energy as a gravitational collapse in which a single neutron star is formed. More than 10^{53} ergs in neutrino-antineutrino pairs is radiated away within ~ 10 s of the collision. The annihilation of a small fraction of the neutrino-antineutrino pairs close to the surface of a neutron star deposits up to 10^{50} ergs in electron-positron pairs (Goodman, Dar, & Nussinov 1987). This must drive a highly super-Eddington wind, with a kinetic energy of up to $\sim 10^{50}$ ergs (Paczyński 1990b and references therein). This is about as much energy as an ordinary supernova releases during the explosion, so there must be some serious consequences for the environment.

Collisions between two neutron stars were suggested as possible gamma-ray bursters (Paczyński 1986; Goodman, Dar, & Nussinov 1987; Eichler et al. 1989; Paczyński 1990b, 1991). Unfortunately, it is currently impossible to estimate the efficiency of X-ray/gamma-ray emission from such a collision. The efficiency may be very low, with most neutrino-antineutrino annihilation energy coming out as the kinetic energy of the baryonic wind. It is much easier to estimate the emission from a related process: a collision of two strange stars. This should produce a very strong gamma-ray burst, with no "baryonic pollution," and should be easily detectable out to a distance of 1 Gpc.

Strange matter made of quarks may be the ground state of matter, and neutron stars with a sufficiently high central density may transform themselves into strange stars (Witten 1984; Haensel, Zdunik, & Schaeffer 1986; Alcock, Farhi, & Olinto 1986). The existence of such stars cannot be proven or disproven at this time. If they exist, then close binaries made of pairs of strange stars should exist as well, and the two com-

[1] Princeton University Observatory, Princeton, NJ 08544.
[2] N. Copernicus Astronomical Center, ul. Bartycka 18, 00-716 Warszawa, Poland.

1991ApJ...375..209H

ponents will collide as a result of the binary orbit decay. Strange stars may have very thin crusts of $\sim 10^{-5}\ M_\odot$ made of ordinary matter. Even if present, such a crust is likely to evaporate due to strong tidal heating in the final phases of the binary orbit decay. A collision may produce a single, rapidly rotating, hot, and bare strange star.

The purpose of this paper is to explore physical processes at the surface of a very hot strange star, in order to find how likely it is to obtain a strong gamma-ray emission. The following § 2 presents astrophysical framework for this scenario, applicable not only to strange stars, but also to ordinary neutron stars. The description of physical processes near the surface of a hot and bare strange star is given in § 3. Finally, the unsolved problems and possible applications to gamma-ray bursts are discussed in § 4.

2. MERGERS/COLLISIONS OF NEUTRON STARS AND STRANGE STARS

A merger/collision of a pair of neutron stars is a powerful source of gravitational radiation. This was a subject of many theoretical studies (Thorne 1987 and references therein). For us, gravitational radiation is important only as an agent that makes the mergers/collisions possible.

A close binary made of two compact stars loses energy and angular momentum through gravitational radiation, and as a consequence the binary orbit gets shorter and the separation between the two components decreases. The rate of gravitational radiation losses is given by the well-known formula (Landau & Lifshitz 1975, p. 356). Approximating the two stars by two point masses of $M_1 = M_2 = M = 1.4\ M_\odot$, the time for them to merge may be calculated to be

$$t_{\rm GR} = -\frac{3}{8}\frac{P_{\rm bin}}{\dot{P}_{\rm bin}} = \frac{405}{2}\frac{GM}{c^3}\left(\frac{a}{6r_g}\right)^4$$

$$= 1.4 \times 10^{-3}\left(\frac{a}{6r_g}\right)^4 \text{ s} = 7.3 \times 10^4 P_{\rm bin}^{8/3} \text{ s} , \quad (1)$$

where $P_{\rm bin}$ is the binary period (in seconds), $r_g = 2GM/c^2 = 4.16 \times 10^5$ cm is the gravitational radius of a 1.4 $M_\odot$ star, a is the separation between the two-point masses, and the orbit is assumed to be circular.

Of course, by the time the separation between the two stars is a few gravitational radii, the relativistic effects on the binary dynamics become very important, and equation (1), as well as all other equations in this section, have to be treated as rough estimates only.

The ratio of the gravitational radiation time scale $t_{\rm GR}$ to the binary period is

$$\frac{t_{\rm GR}}{P_{\rm bin}} = \frac{135}{16\pi\sqrt{6}}\left(\frac{a}{6r_g}\right)^{2.5} = 1.096\left(\frac{a}{6r_g}\right)^{2.5} , \quad (2)$$

independent of the stellar mass (assuming $M_1 = M_2$). Notice, that orbit decay time is about equal to the binary period when the two neutron stars are about to contact each other. This implies that a merger of two neutron stars is a collision rather than a gentle fusion. In particular, there is no time for the Roche lobe overflow that might lead to the explosion of the lower mass neutron star (see Colpi, Shapiro, & Teukolsky 1989, 1991, and references therein). Even the concept of a Roche lobe is not applicable, as the two stars cannot co-rotate with the binary: the orbital period decreases so rapidly that tidal interactions cannot enforce co-rotation.

The tides may not be able to synchronize stellar rotation with the binary orbit, but they may provide a very strong heating for the star. Let us assume that the neutron star is kept in synchronous rotation with the current binary period. This implies that the rotational energy of the star is changing at the rate

$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega} = -4\pi^2 I P_{\rm bin}^{-3}\dot{P}_{\rm bin} = \frac{I}{10 \times 6^6}\frac{c^9}{G^3M^3}\left(\frac{a}{6r_g}\right)^{-7}$$

$$\approx 0.7 \times 10^{55}\left(\frac{a}{6r_g}\right)^{-7} \text{ ergs s}^{-1} , \quad (3)$$

where $I \approx 10^{45}$ g cm^2 is the moment of inertia of a neutron star. This rate may be compared with the rate at which gravitational radiation changes the energy of the whole binary system:

$$\dot{E}_{\rm bin} = -\frac{1}{15 \times 6^5}\frac{c^5}{G}\left(\frac{a}{6r_g}\right)^{-5}$$

$$\approx 1.9 \times 10^{55}\left(\frac{a}{6r_g}\right)^{-5} \text{ ergs s}^{-1} . \quad (4)$$

So far all our analysis applies to any compact stars, neutron as well as strange. If the surface layers of a compact star are made of ordinary matter then the heat deposition rate by the tides at the final phases of the binary orbit decay may become super-Eddington. The Eddington luminosity for a 1.4 $M_\odot$ star with no hydrogen in its atmosphere is $L_{\rm Edd} = 3.5 \times 10^{38}$ ergs s^{-1}. Therefore, the rate of change of the rotational energy implied by co-rotation (see eq. [3]) is

$$\frac{\dot{E}_{\rm rot}}{L_{\rm Edd}} \approx 2 \times 10^{16}\left(\frac{a}{6r_g}\right)^{-7} \approx \left(\frac{4 \text{ s}}{P_{\rm bin}}\right)^{14/3} \approx \left(\frac{1 \text{ month}}{t_{\rm GR}}\right)^{7/4} . \quad (5)$$

The equation (5) gives an upper limit to the rate of rotational energy change. However, it is so enormous that even very inefficient tides are likely to deposit heat at the highly super-Eddington rate into the outermost layers of the two binary components. The two stars may become bright X-ray sources in the last month of the binary existence, when the binary period is shorter than 4 s. It is likely, that just prior to the merging the super-Eddington heat deposition rate drives a strong wind and removes the surface layers. Quantitative analysis of these processes is beyond the scope of this paper.

If the two components of the binary are strange stars covered with a thin layer of ordinary matter, $\sim$400 m thick and containing no more than $\sim 10^{-5}\ M_\odot$ (Miralda-Escudé, Haensel, & Paczyński 1990, and references therein), then it is possible that this thin layer is expelled due to the tidal heating just prior to the merger, and a bare strange surface is exposed. If the ejection of ordinary matter is not completed prior to the merger then the initial, very violent phases of the merger may eject the rest. At this time we cannot prove that the merged strange star must be bare, but we think this is a reasonable possibility. As this is also the simplest possibility, it will be considered in some details in the following section.

The physics of merger/collision is very complicated, but the following scenario seems reasonable to us.

For some days or weeks prior to the merger tidal heating makes the two compact stars strong X-ray sources. Just prior to the merger mass loss is induced by the intense tidal heating, and X-ray emission is likely to fade away, obscured by the optically thick wind.

The initial merger/collision lasts for a dynamical time scale, ~ 1 ms, and most kinetic and gravitational energy is likely to be thermalized on this time scale. On a somewhat longer time scale, gravitational radiation makes the merged object axially symmetric. However, it will be differentially rotating. On a much longer viscous time scale, rigid body rotation is enforced. It is likely that this object, with a mass of $\sim 2 \times 1.4\ M_\odot$, is above the Oppenheimer-Volkoff limit for rigidly rotating strange stars and that it will eventually collapse into a black hole. We hope that this object may remain stable against the collapse as long as differential rotation is important, by analogy with differentially rotating white dwarfs (Tassoul 1978, p. 370, and references therein). Even uniform rotation might increase the maximum mass of strange stars by $\sim 30\%$ (Lattimer et al. 1990).

The thermal energy of $\sim 10^{53}$ ergs produced in the merger/collision is radiated away in a burst of neutrino-antineutrino emission that lasts a few seconds. If there is an ordinary baryonic matter left at the surface of the object then a highly super-Eddington wind is likely to absorb most energy deposited in the neutrino-antineutrino annihilations (Paczyński 1990b). However, if the merged object is a bare strange star than most of the annihilation energy will be transformed into gamma rays. This is the subject of the following section.

3. PHYSICAL PROCESSES AT THE HOT STRANGE SURFACE

A collision/merger of two strange stars thermalizes kinetic energy of collision, which is comparable to the binding energy of the system, i.e., roughly a few times 10^{53} ergs. A typical Fermi energy of quarks in a strange star exceeds 300 MeV, and therefore strange matter is strongly degenerate even at the temperatures as high as 10^{11} K. Approximating strange matter by the free Fermi gas of the ultrarelativistic quarks with 18 internal degrees of freedom: 3 flavors $\times$ 3 colors $\times$ 2 spins (see Iwamoto 1982), the thermal energy $E_{\rm th}$ can be related to the internal temperature of the star by the formula

$$E_{\rm th} \simeq 5 \times 10^{51} \left(\frac{n_b}{n_0}\right)^{2/3} R_6^3 T_{11}^2 \text{ ergs} , \tag{6}$$

where n_b is the average baryon density of a strange star, n_0 is the normal nuclear matter density, $n_0 = 0.15 fm^{-3} = 1.5 \times 10^{38}$ cm^{-3}, R_6 is the stellar radius in units of 10^6 cm, and $T_{11} = T/10^{11}$ K. The internal temperature of the newly born strange star is therefore estimated as

$$T_{11} \simeq 5 \left(\frac{n_b}{n_0}\right)^{-1/3} R_6^{-3/2} (E_{\rm th\ 53})^{1/2} . \tag{7}$$

Adopting $E_{\rm th\ 53} = E_{\rm th}/10^{53}$ ergs $= 1$, $n_b = 4n_0$, $R_6 = 1$, we obtain $T_{11} \simeq 3$. This estimate of the initial internal temperature will be used in our subsequent considerations.

3.1. *Neutrino Burst: Diffusion Stage*

Newly born strange star cools by the emission of neutrinos and antineutrinos. At the temperature in excess of 10^{11} K the mean free path of neutrinos in the strange matter is much smaller than the stellar radius, and the time scale for neutrinos to diffuse out is a few seconds, much longer than the dynamical time scale. The heat transport in the interior of strange star with $T_{11} \simeq 3$ is due mainly to the diffusion of the mu (ν_μ, $\bar\nu_\mu$) and tau (ν_τ, $\bar\nu_\tau$) neutrinos, limited by the neutral current scattering on quarks. The mean free paths for ν_e and $\bar\nu_e$, limited by the charged current absorption processes, are significantly shorter than those for μ and τ ones. In what follows, we shall calculate the neutrino mean free paths in quark matter using the formulae derived by Iwamoto (1982), with the choice of the electron fraction, $Y_e = n_e/n_b$, and of baryon number density, approximate for a typical model of strange star: $Y_e = 10^{-4}$, $n_b = 4n_0$ (see Haensel, Zdunik, & Schaeffer 1986).

The energy transport by the diffusion of the μ and τ neutrinos is determined by the Rosseland mean free path, $\lambda_\mu = \lambda_\tau$, as defined by Sawyer & Soni (1979). For our model we get $\lambda_\mu = 1.8 \times 10^4/T_{11}^3$ cm, so that for the initial configuration, with $T_{11} \simeq 3$, we obtain $\lambda_\mu = 7 \times 10^2$ cm. In order to find the neutrino luminosity of the newly born massive strange star, we considered a very simple stellar model of the constant baryon density $n_b = 4n_0$. The simplicity of the model is justified by the exploratory character of the present study. The heat transport in the stellar interior, mediated by the diffusion of μ and τ neutrinos, was described by the diffusion equation

$$c_v \frac{\partial T}{\partial t} = -\frac{1}{4\pi r^2}\frac{\partial l_\nu}{\partial r} , \quad l_\nu = -4\pi r^2 \frac{28}{3} \sigma \lambda_\mu T^3 \frac{\partial T}{\partial r} , \tag{8}$$

where $c_v = 2.3 \times 10^{22} (n_b/n_0)^{2/3} T_{11}$ ergs cm^{-3} K^{-1} is the specific heat of strange matter (Iwamoto 1982), and l_ν is the diffusive neutrino luminosity.

The diffusion of the electron neutrinos is limited by the charged current absorption on quarks. The Rosseland mean free path, as defined in Sawyer & Soni (1979), reads then $\lambda_e = 1.3 \times 10^3/T_{11}^2$ cm, so that the electron neutrinosphere will lay well above the μ-τ one and very close to the strange star surface. The temperature profile between the μ-τ and the electron neutrinospheres is determined by the heat transport mediated by the μ and τ neutrinos. Most of neutrino energy is lost while at the stellar surface $T_{11} \simeq 1$, hence the mean free path of the electron neutrinos is about one order of magnitude shorter than the mean free path of the μ and τ neutrinos, hence the electron neutrinosphere lies at almost zero optical depth for the μ and τ neutrinos. Using Eddington approximation the electron neutrinosphere temperature, T_e, is related to T_μ by the relation: $T_e^4 = 0.5 \times T_\mu^4$.

We assume that μ and τ neutrinos are emitted at the μ-τ neutrinosphere, with the radius approximately equal to the stellar radius, $R_\mu = R_\tau \approx R$. Taking into account the number of neutrino species we obtain the total neutrino luminosity

$$\begin{aligned} L_\nu &= 4\pi R^2 \frac{7\sigma}{8} (2T_\mu^4 + T_e^4) \\ &= 1.56 \times 10^{53} T_{\mu 11}^4 R_6^2 \text{ ergs s}^{-1} . \end{aligned} \tag{9}$$

Therefore, the boundary condition at $R_\mu = R$ may be written as

$$\left(\frac{\partial T}{\partial r}\right)_R = -\frac{15}{64}\left(\frac{T}{\lambda_\mu}\right)_R , \tag{10}$$

where L_ν was calculated assuming $T_\mu = T(R)$.

As the initial conditions we adopted a uniform distribution of temperature in the newly formed strange star, with $T_{0,11} = 3$. This corresponds to the initial thermal energy of the star $E_{\rm th,0} = 1.09 \times 10^{53}$ ergs. This is entirely ad hoc, but has a virtue of being simple. The diffusion equation (8) was solved numerically, subject to the outer boundary condition given by the equation (10).

The initial neutrinosphere temperature of 3×10^{11} K dropped very rapidly, and the cooling front moved into the

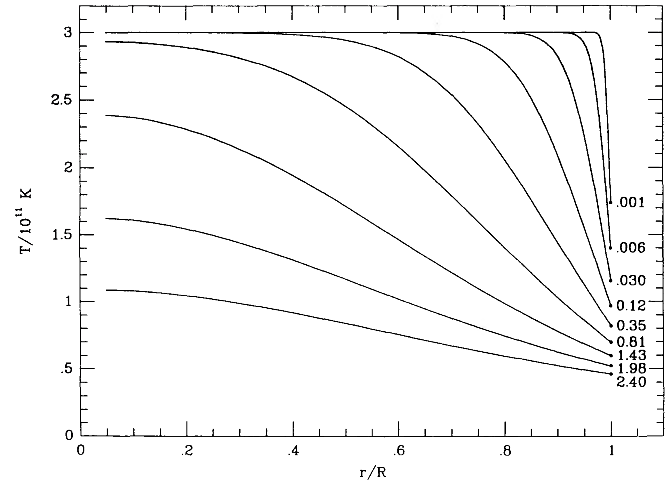

FIG. 1.—The temperature as a function of radius is shown with solid lines labeled with the time (in seconds) that has elapsed since the merger/collision of two strange stars. The rightmost point of the curves corresponds to the μ-τ neutrinosphere. The initial temperature was adopted to be 3×10^{11} K, uniform throughout the star. Notice the early development of the cooling front.

star, as shown in Figure 1. The variation of the surface and the central temperature with time is shown in Figures 2*a* and 2*b*. After 2 s the temperature of the μ-τ neutrinosphere dropped to $T_{\mu 11} = 0.5$, while the central temperature decreases by a factor of 2, to $T_{c11} = 1.5$.

The dynamical time scale of a strange star is a fraction of a millisecond. We expect that most of the kinetic energy dissipates into heat during the first millisecond after the collision. The process is certainly very complicated, and we make no attempt to follow it. Therefore, we ignored the first millisecond of thermal evolution away from the initially uniform temperature distribution, during which the neutrinosphere temperature dropped from 3×10^{11} K to 1.7×10^{11} K. During this time interval only a small fraction of all thermal energy was lost with neutrinos, but as these were the highest energy neutrinos, they deposited about as much energy into the pair

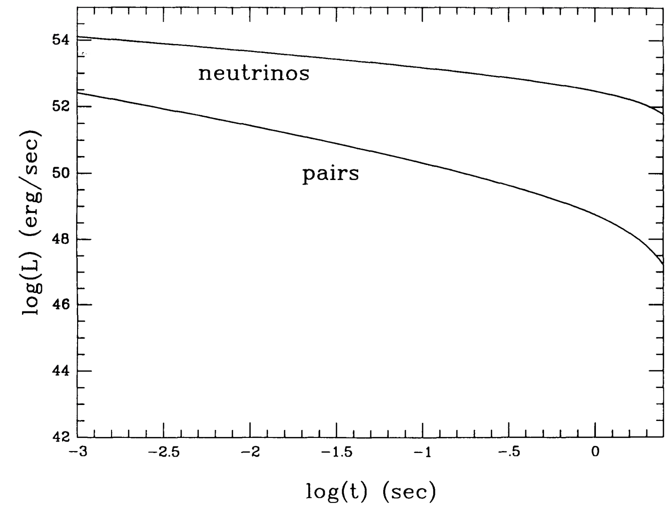

FIG. 3.—Neutrino and pair plasma luminosities, L_ν and $L_{\rm pairs}$, are shown as a function of time.

plasma, as did all the subsequent evolution. We shall discuss this problem in the last section of this paper.

The variation of the neutrino luminosities during the first 2.5 s is shown in Figure 3. The integrated neutrino luminosity, $E_\nu(t) = \int_{1\,\rm ms}^{t} L_\nu \, dt'$, is shown in Figure 4. Fifty percent of the initial thermal energy was lost with the neutrinos during the first 0.4 s, while during the first 2 s the strange star lost 90% of its initial thermal energy.

3.2. *Energy Injection above the Strange Star Surface*

Because of the huge number density of neutrinos in the initial neutrino burst, the process of the neutrino par annihilation $\nu\bar{\nu} \rightarrow e^+e^-$ operates in the region close to the strange star surface. Neutrino pair annihilation will very slightly deplete the neutrino flux, producing an ultrarelativistic e^+e^- plasma. Inside the strange star, in the layer between the neutrinosphere and the strange matter surface, this process is strongly quenched by the degeneracy of the electrons ($\mu_e \sim 30$ MeV). Only a small fraction of neutrinos will be converted into

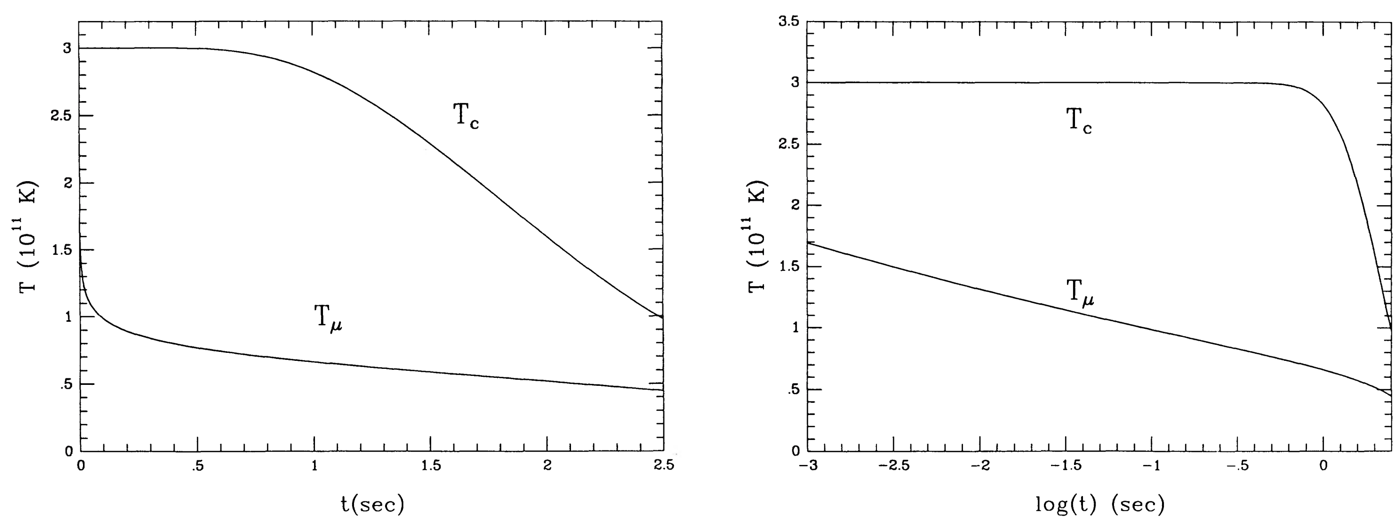

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*–*b*) The time dependence of the μ-τ neutrinosphere temperature, T_μ, and of the central temperature of the strange star, T_c

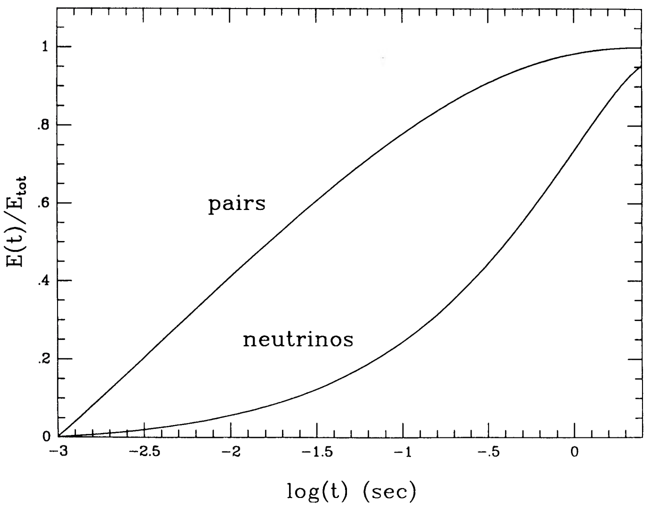

FIG. 4.—The variation of the integrated neutrino and pair plasma energy, $E = \int_{1\,\mathrm{ms}}^{t} L\,dt'$, with time. Energy radiated during the first millisecond after the merger/collision has been ignored. The total neutrino energy radiated during the whole burst is equal to the initial thermal energy of the merged star, $E_{\nu,\mathrm{tot}} = E_{\mathrm{th},0} \approx 10^{53}$ ergs $(T_0/3 \times 10^{11}\ \mathrm{K})^2$. The total energy deposited in the pair plasma is $E_{\mathrm{pairs,tot}} \approx 1.5 \times 10^{50}$ ergs $\times\ (T_0/3 \times 10^{11}\ \mathrm{K})^4$. The time scale on which 90% of the plasma energy is injected is insensitive to the choice of the initial temperature T_0, and it is always ~ 0.2 s.

the e^+e^- pairs. Therefore, the temperature of the thermalized e^+e^- plasma will be significantly lower than the neutrinospheres temperatures.

Using the formula (A6), derived in the Appendix, we can write the expression for the energy deposition (injection) rate in a shell of the thickness hR above the strange star surface as

$$\Delta \dot{E}_{\nu\bar{\nu}}(h) = 1.22 \times 10^{50}(T_{\mu 11}^9 + 4.5T_{\nu_e}^9)\alpha(h)\ \mathrm{ergs\ s^{-1}}\ , \qquad (11)$$

where the numerically calculated function $\alpha(h)$ is shown in Figure 5. As one can see from Figure 5, more than 90% of the e^+e^- energy is injected within $0.3R$ above the strange star surface. Using the approximate relation $T_e^4 = T_\mu^4/2$, we can calculate the total energy injection rate above the strange star

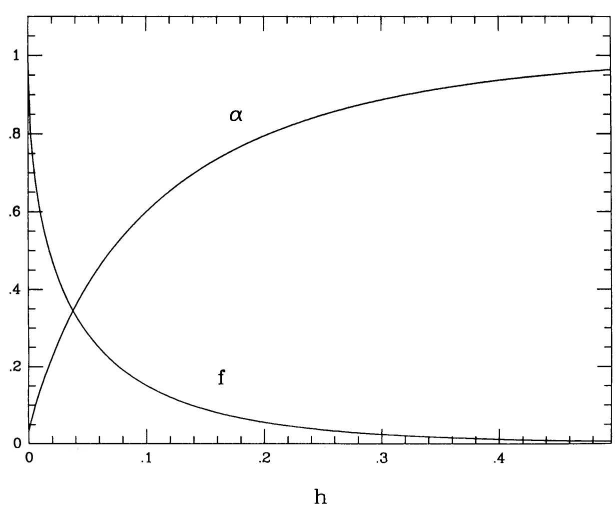

FIG. 5.—Dimensionless functions $f(h)$ and $\alpha(h)$, entering the expressions for the e^+e^- deposition above the surface of the strange star.

surface

$$L_{\mathrm{pairs}} = 2.3 \times 10^{50} T_{\mu 11}^9 R_6^3\ \mathrm{ergs\ s^{-1}}\ . \qquad (12)$$

Using our results for the thermal evolution of the newly born massive strange star, we get the total energy injected above the stellar surface in the form of the e^+e^- plasma after 1 ms,

$$E_{\mathrm{pairs}} = \int_{1\,\mathrm{ms}}^{\infty} L_{\mathrm{pairs}}\,dt = 1.5 \times 10^{50}\ \mathrm{ergs}\ . \qquad (13)$$

The variation of the pair luminosity, L_{pairs}, and the variation of the integrated pair luminosity, $E_{\mathrm{pairs}}(t) = \int_{1\,\mathrm{ms}}^{t} L_{\mathrm{pairs}}\,dt'$, with time is shown in Figures 3 and 4. As the neutrino pair annihilation rate is proportional to the very high power of the neutrinosphere temperature, $L_{\mathrm{pairs}} \propto T_\mu^9$, the effective duration of the e^+e^- injection is very short. Fifty percent of the pair plasma energy is injected in just 16 ms, 90% is injected in 0.2 s, and 99% is injected in 1 s.

The total energy of the pair plasma is very sensitive to the neutrinosphere temperature of the strange star. If we included the energy deposited in the first millisecond after the collision, the energy would be almost twice as large as given with the equation (13). Let us notice, that if the initial temperature was 5.8×10^{11} K, then the energy deposited in the pair plasma after 1 ms would be equal to the estimate of Goodman, Dar, & Nussinov (1987), $E_{\mathrm{pairs}} \approx 2 \times 10^{51}$ ergs, who considered a specific scenario of pair deposition accompanying the birth of a *neutron* star. The average energy of the e^+e^- pair produced in the $\nu_\mu \bar{\nu}_\mu$ annihilation (before equilibration) depends rather weakly on h. At $h = 0.1$ we obtain $\langle \epsilon_{e^+} + \epsilon_{e^-} \rangle \simeq 8k_B T_\nu$. The average pair energy in the equilibrated e^+e^- plasma is initially lower by a factor of ~ 5, the degradation factor increasing with time.

4. DISCUSSION

Our simplified model of a cooling strange star demonstrated that most of thermal energy is lost with neutrinos and antineutrinos within ~ 2 s after the merger/collision between the two stars. The most drastic simplifications were the adoption of a spherical symmetry and the constant initial temperature. The only reason for this choice was the simplicity of the model. A real object would be vastly more complex.

The dynamical merger/collision may take ~ 1 ms. On that time scale most of the kinetic energy would be converted into heat, and fully three-dimensional object would undergo violent oscillations, damped by gravitational radiation and viscosity of strange matter. It is likely that a large fraction of mechanical energy would be dissipated into heat over a damping time scale, that is much longer than 1 ms (Cutler, Lindblom, & Splinter 1990). There is no reason to expect uniform temperature over the whole volume of the merged star, only one heating episode, or any symmetry.

As complicated as the merged star may be, some things are likely to be simple. The overall cooling time is not likely to be vastly different than that of the spherical model. However, the fraction of neutrino-antineutrino pairs that will annihilate into the electron-positron plasma and gamma rays is proportional to the ninth power of the surface temperature. Therefore, the energy deposited in the pair plasma is very sensitive to the details of the dissipation of mechanical energy into heat. This is unfortunate, as we are interested in the energy available for the creation of the pair plasma.

Within our approximations we find that the total energy of the pair plasma injected after the first millisecond, $E_{\rm pairs}$, scales as $E_{\rm pairs} \simeq 1.5 \times 10^{50}$ ergs $\times (T_0/3 \times 10^{11}$ K$)^4 \cong 1.5 \times 10^{50}$ ergs $\times (E_{\rm th0}/10^{53}$ ergs$)^2$. The time scale on which 90% of the plasma energy is injected is insensitive to the choice of the initial temperature, and it is always ~ 0.2 s.

Our model demonstrates that the heat diffusion cools the outermost layers of the star and makes the model unstable against the convection. We made no estimate of the efficiency of the convective heat transport. However, the sign of the effect is clear. Convection would raise the surface temperature, shorten the cooling time and most likely would increase the rate of energy deposition in the pair plasma.

As uncertain as the model is, we think it is reasonable to expect that of the order of 10^{50} ergs will be deposited in the pair plasma around the merged binary on a time scale of ~ 0.2 s. All electron-positron pairs will annihilate into gamma rays. The power of gamma-ray emission will be $\sim 10^{51}$ ergs s^{-1} from a surface of $\sim 4\pi \times 10^{12}$ cm^2. At this energy density the pair plasma will be thermalized and will produce a fireball with the effective temperature of $\sim 3 \times 10^{10}$ K (Paczyński 1986; Goodman 1986), i.e., a roughly blackbody spectrum peaking at energies $E_\gamma \approx 8$ MeV. An event like that at a distance of 1 Gpc would be easily detectable as a short gamma-ray burst with a fluence of $S \approx 10^{-6}$ ergs cm^{-2}.

All the complications due to nonsphericity and rapid oscillations, extended in time conversion of mechanical energy into heat, could extend the duration of the gamma-ray burst, provided it with some time structure, and broaden the blackbody spectrum. Also, the total energy expected in gamma rays may easily be one order of magnitude more or less than 10^{50} ergs. Still, with all these uncertainties, a merger/collision of two strange stars is most likely to give rise to a short gamma-ray burst detectable at a cosmological distance.

It is expected that BATSE experiment on the *Gamma Ray Observatory* will provide the information about the angular distribution of weak gamma-ray bursts and will establish beyond any reasonable doubt the distance scale to gamma-ray bursters (see Paczyński 1990a, 1991, and references therein). If the balloon data of Meegan, Fishman, & Wilson (1985) are to be taken seriously then the change in the slope of the burst counts, i.e., in the log N–log $N_{\rm max}$ relation, may be just below the detection threshold of the current generation of spaceborne experiments, i.e. it may correspond to the fluence of $\sim 10^{-6}$ ergs cm^{-2}. If the bursts weaker than this limit are distributed isotropically, than the break in the slope of the counts should correspond to a cosmological distance, i.e., a fair fraction of the Hubble distance, like a few gigaparsecs. This in turn would imply the intrinsic burst energy in the range of 10^{50}–10^{51} ergs. This is the range that may be expected from the collision between two strange stars, but most likely in excess of what is expected from a collision between two neutron stars (Paczyński 1990b, and references therein).

Within our crude model the duration of gamma-ray bursts expected from the strange star collisions is very short, a fraction of a second. Some gamma-ray bursts are that short, but many bursts are much longer. It is not clear if the complications in merger/collisions can prolong the duration of the burst. We see no convincing way of doing this.

The existence of strange stars is only a speculation at this time. Nevertheless, we would like to check if the theoretical scenario proposed in this paper does not have some obvious inconsistencies. One of the problems for the strange and the neutron stars alike is a possibility that the merged object may collapse into a black hole. We are not aware of any calculations of the upper mass limit for a differentially rotating strange or neutron star, with the general relativity fully taken into account. It is not unreasonable to expect that as long as the merged object is differentially rotating it may be stable against the collapse. According to Haensel & Jerzak (1989) the shear viscosity of strange matter is $\eta \simeq 10^{15} T_{11}^{-2}$ g cm^{-1} s^{-1}. The time scale on which differential rotation will be suppressed is therefore

$$t_{\rm visc} \simeq \frac{R^2 \rho}{\eta} \simeq 10^{12} T_{11}^2 \ {\rm s}\,, \tag{14}$$

i.e., it is so long that it is of no concern to us. Even a uniform but rapid rotation rises the maximum mass for strange stars by as much as 30% (Lattimer et al. 1990).

At the surface of a strange star neutrons may evaporate. This process will very rapidly cool the outer layer with the thickness comparable to the heat transport mean free path for quarks, which is $\sim 10^{-9} T_{11}^{-1}$ cm (Haensel & Jerzak 1989). However, as soon as the surface cools to $T_{\rm surf} < 0.1 \Delta\mathscr{E}/k_B$, where $\Delta\mathscr{E} \approx 20$–40 MeV is the binding energy of neutrons in strange matter (Farhi & Jaffe 1984), i.e., as soon as $T_{11,\,\rm surf} < 0.2$–0.4, neutron evaporation becomes negligible. Notice that this process will not affect the conditions at the neutrinosphere, which is located at a depth $\sim 10^2$ cm $\gg 10^{-9}$ cm.

The possibility of boiling of strange matter into nucleon vapor at low pressure has been advanced by Alcock & Olinto (1989). However, the increase of pressure suppresses boiling. Combining the criterion of Alcock & Olinto (1989) with the model of hot strange matter of Chmaj & Slominski (1989), we find that the boiling is energetically possible only within the outermost 5 m below the stellar surface, but only provided the temperature there is high enough, $T_{11} > 1$. According to Madsen & Olesen (1990) boiling of a hot strange matter is much more difficult and may be unimportant for us. We conclude that the baryonic polution of the strange star environment, during the most of the neutrino burst, by evaporation and boiling is insignificant.

Photon emission from a strange surface is strongly suppressed because the plasmon energy is very high inside a strange star, $E_{\rm plas} \approx 20$ MeV (Alcock, Farhi, & Olinto 1986). As a result, the strange surface acts as almost perfect mirror for photons with energies below $\sim E_{\rm plas}$; i.e., its emissivity is almost zero, while for photons with higher energies the surface radiates like a blackbody. Detailed calculation (Haensel 1991) shows that at the surface temperatures considered the surface photon luminosity is small compared to the energy injection rate due to the $\nu\bar{\nu}$ annihilation.

We conclude that the mergers/collisions of strange stars are natural sites of very powerful gamma-ray bursts. If short and hard gamma-ray bursts are detected at distances ~ 1 Gpc, then the explanation in terms of strange stars would be the least speculative.

This project was supported by the NASA grant NAGW-765 and NSF grant AST-8718432.

APPENDIX

Let us consider the case of neutrinos of one flavor "f," emitted from the neutrinosphere of temperature $T_{\nu f}$, of radius R. We denote the momenta of colliding ν_f and $\bar{\nu}_f$ by $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$, and those of created e^- and e^+ by $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$. Summing over all initial and final states we obtain following formula for the energy deposition rate per unit volume at the height $H = hR$ over the strange star surface:

$$\epsilon_f(h) = \int \frac{d^3q_1}{(2\pi\hbar)^3} \int \frac{d^3q_2}{(2\pi\hbar)^3} f_{\nu f}(q_1) f_{\bar{\nu} f}(q_2) \times \int \frac{d^3p_1}{(2\pi\hbar)^3} \int \frac{d^3p_2}{(2\pi\hbar)^3} W(\boldsymbol{q}_1\boldsymbol{q}_2, \boldsymbol{p}_1\boldsymbol{p}_2)[1 - f_{e^-}(p_1)][1 - f_{e^+}(p_2)] \,. \tag{A1}$$

The angular integrations over $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$, the momenta of ν_f and $\bar{\nu}_f$ emitted from the neutrinosphere, are performed within a cone with the apex at the point under consideration, the surface of which is tangent to the stellar surface. W is the transition rate for the process $\nu_f + \bar{\nu}_f \rightarrow e^+ + e^-$. Fermi-Dirac distribution functions f with the zero chemical potential are

$$f_{\nu f}(q) = \left[\exp\left(\frac{q}{k_B T_{\nu f}}\right) + 1\right]^{-1}, \qquad f_e(p) = \left[\exp\left(\frac{\epsilon_p}{k_B T_e}\right) + 1\right]^{-1}, \tag{A2}$$

where T_e is the temperature of the equilibrated e^+e^- plasma. As T_e is significantly lower than the neutrinosphere temperature, we can neglect the effect of blocking of the final e^+e^- states in equation (A1). This simplifies considerably the calculation of $\epsilon_f(h)$.

After calculating W within the framework of the standard electroweak interaction model we get

$$\epsilon_f(h) = \frac{2G^2(k_B T)^9}{3(2\pi)^5 \pi \hbar^{10} c^9} C_f F(h) \,, \tag{A3}$$

where $C_e = 4 \sin^4 \Theta_W + 2 \sin^2 \Theta_W + \frac{1}{2}$, $C_\mu = C_\tau = 4 \sin^4 \Theta_W - 2 \sin^2 \Theta_W + \frac{1}{2}$, and the experimental values are $\sin^2 \Theta_W = 0.23$, $G = 1.4358 \times 10^{-49}$ ergs cm^3. The dimensionless function $F(h)$ was calculated by numerical integration. We found that $F(0) = 1.247 \times 10^3$. The function $f(h) = F(h)/F(0)$ is shown in Figure 5. Putting in all the numerical coefficients we obtain

$$\epsilon_f(h) = 1.53 \times 10^{32} T_{\nu f 11}^9 D_f f(h) \text{ ergs s}^{-1} \text{ cm}^{-3} \,, \tag{A4}$$

where $D_\mu = D_\tau = 1$, $D_e = 4.54$.

The energy deposition rate within a spherical shell of thickness hR above the strange star surface is calculated as

$$\Delta \dot{E}_{\nu f \bar{\nu} f}(h) = 4\pi R^3 \int_0^h (1 + h')^2 \epsilon_f(h') dh' \,, \tag{A5}$$

which can be expressed in a form suitable for applications,

$$\Delta \dot{E}_{\nu f \bar{\nu} f}(h) = 1.2 \times 10^{50} D_f T_{\nu f 11}^9 R_{\nu 6}^3 \alpha(h) \text{ ergs s}^{-1} \,, \qquad \alpha(h) = \frac{\int_0^h (1 + h')^2 f(h') dh'}{\int_0^\infty (1 + h')^2 f(h') dh'} \,. \tag{A6}$$

The function $\alpha(h)$ is plotted in Figure 5.

REFERENCES

Alcock, C., Fahri, E., & Olinto, A. 1986, ApJ, 310, 261
Alcock, C., & Olinto, A. 1989, Phys. Rev., D39, 1233
Anderson, S. B., Gorham, P. W., Kulkarni, S. R., Prince, T. A., & Wolszczan, A. 1990, Nature, 346, 42
Chmaj, T., & Slominski, W. 1989, Phys. Rev., D40, 165
Clark, J. P. A. 1979, in Sources of Gravitational Radiation, ed. L. Smarr (Cambridge: Cambridge Univ. Press), p. 447
Clark, J. P. A., & Eardley, D. M. 1977, ApJ, 215, 311
Clark, J. P. A., van den Heuvel, E. P. J., & Sutantyo, W. 1979, A&A, 72, 120
Colpi, M., Shapiro, S. L., & Teukolsky, S. A. 1989, ApJ, 339, 318
———. 1991, ApJ, 369, 422
Cutler, C., Lindblom, L., & Splinter, R. J. 1990, ApJ, 363, 603
Dyson, F. J. 1963, in The Search for Extraterrestial Life, ed. A. G. W. Cameron (New York: Benjamin), p. 119
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Farhi, E., & Jaffe, R. L. 1984, Phys. Rev., D30, 2379
Gilden, D. L., & Shapiro, S. L. 1984, ApJ, 287, 728
Goodman, J. 1986, ApJ, 308, L47
Goodman, J., Dar, A., & Nussinov, S. 1987, ApJ, 314, L7
Haensel, P. 1989, unpublished
———. 1991, in Proc. Workshop on Strange Matter (Aarhus, Denmark; 1991 May), in press
Haensel, P., & Jerzak, A. J. 1989, Acta. Phys. Polonica, B20, 141
Haensel, P., Zdunik, J. L., & Schaeffer, R. 1986, A&A, 160, 121
Iwamoto, N. 1982, Ann. Phys., 141, 1
Landau, L. D., & Lifshitz, E. M. 1975, The Classical Theory of Fields (New York: Pergamon)
Lattimer, J. M., Mackie, F., Ravenhall, D. G., & Schramm, D. N. 1977, ApJ, 213, 225
Lattimer, J. M., Prakash, M., Masak, D., & Yahil, A. 1990, ApJ, 355, 241
Lattimer, J. M., & Schramm, D. N. 1974, ApJ, 192, L145
———. 1976, ApJ, 210, 549
LeBlanc, J. M., & Wilson, J. R. 1970, ApJ, 161, 541
Madsen, J., & Olesen, M. L. 1991, Phys. Rev. D, in press
Meegan, C. A., Fishman, G. J., & Wilson, R. B. 1985, AJ, 291, 479
Meier, D. L., Epstein, R. I., Arnett, W. D., & Schramm, D. N. 1976, ApJ, 204, 869
Meyer, B. S. 1989, ApJ, 343, 254
Miralda-Escudé, J., Haensel, P., & Paczyński, B. 1990, ApJ, 362, 572
Ostriker, J. P. 1979, in Sources of Gravitational Radiation, ed. L. Smarr (Cambridge: Cambridge Univ. Press), p. 461
Paczyński, B. 1986, ApJ, 308, L43
———. 1990a, ApJ, 348, 485
———. 1990b, ApJ, 363, 218
———. 1991, in Proc. Los Alamos Workshop on Gamma-Ray Bursts, in press
Quinlan, G. D., & Shapiro, S. L. 1989, ApJ, 343, 725
Sawyer, R. F., & Soni, A. 1979, ApJ, 230, 859
Schramm, D. N., & Barkat, Z. 1972, ApJ, 173, 195
Slonimski, A., & Chmaj, B. 1988, private communication
Symbalisty, E. M. D. 1984, ApJ, 285, 729
Symbalisty, E., & Schramm, D. N. 1982, Ap. Letters, 22, 143
Tassoul, J.-L. 1978, Theory of Rotating Stars (Princeton: Princeton Univ. Press)
Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 434
Thorne, K. S. 1987, in 300 Years of Gravitation, ed. S. W. Hawking & W. Israel (Cambridge: Cambridge Univ. Press)
Witten, E. 1984, Phys. Rev., D30, 272
Wolszczan, A. 1990, IAU Circ., No. 5073