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TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

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ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be used to estimate the parameters of a transient as a function of poorly known input parameters. The mergers may be detected with high-redshift supernova searches as rapid transients, many of them far away from the parent galaxies. It is possible that the mysterious optical transients detected by Schmidt et al. are related to neutron star mergers, since they typically have no visible host galaxy.

Subject headings: binaries: close — gamma rays: bursts — stars: neutron — supernovae: general

1. INTRODUCTION

Popular models of gamma-ray bursts (GRBs) include merging neutron stars (NS-NS) (Paczyński 1986; Popham, Woosley, & Fryer 1998; and references therein), and merging neutron stars and stellar-mass black holes (NS-BH) (Paczyński 1991; Popham et al. 1998 and references therein). However, the location of the recently detected GRB afterglows indicates that the bursts may be located in star-forming regions (Paczyński 1998; Kulkarni et al. 1998a, 1998b; Taylor et al. 1998; Galama et al. 1998). If this indication is confirmed by the locations of afterglows detected in the future, then the NS + NS and NS + BH merger scenario will be excluded, since those events are expected to occur far away from their place of origin (Tutukov & Yungelson 1994; Bloom, Sigurdsson, & Pols 1998; Zwart & Yungelson 1998).

Still, the mergers are certainly happening, although at a rate estimated to be several orders of magnitude lower than the supernova rate (Narayan, Piran, & Shemi 1991; Phinney 1991; van den Heuvel & Lorimer 1996; Bloom et al. 1998). It is virtually certain that a violent merger will eject some matter with a subrelativistic velocity. The chemical composition of the ejecta must be very exotic, since it is formed by a rapid decompression of nuclear-density matter. Not surprisingly, it has been suggested this process is responsible for some exotic elements (Lattimer & Schramm 1974, 1976; Rosswog et al. 1998 and references therein). As most nuclides are initially very neutron rich, they will decay with various timescales. Therefore, we expect a phenomenon somewhat similar to a Type Ia supernova, in which the decay of ^{56}Ni first to ^{56}Co and later to ^{56}Fe is responsible for the observed luminosity. It is therefore interesting to explore the likely light curves following the NS + NS and/or NS + BH mergers.

Neutron star mergers are expected to be among the first sources of gravitational radiation to be detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) (Abramovici et al. 1992). It will be very important to detect the same events by other means. In the last several years, much effort has gone into obtaining gamma-ray bursts from the mergers. However, theoretical attempts are discouraging (cf. Ruffert & Janka 1997, 1998 and references therein), and the observed locations of the burst afterglows do not favor mergers. The purpose of this paper is to point out that the mergers are likely to be accompanied by prominent optical transients, which should be detectable with future supernova searches, and perhaps have already been detected by Schmidt et al. (1998).

2. OUTLINE OF THE MODEL

Modeling of a NS + NS or a NS + BH merger is very complex, and our knowledge of the outcome is very limited. Therefore, instead of attempting to develop a complete numerical model (Ruffert & Janka 1997, 1998 and references therein) we make the simplest possible substitute, a one-zone model of an expanding envelope. While most of the mass falls into the black hole, some matter is ejected as a result of the complicated hydrodynamics of the merger, or the powerful neutrino burst, or the superstrong magnetic fields. For simplicity, we assume that the expanding envelope is spherical, its mass M is constant with time, and its density ρ is uniform in space and decreases with time. The surface radius R increases at the fixed velocity V; i.e., we ignore the dynamical effect of the pressure gradient. Therefore, the density throughout is given by

$$\rho = \frac{3M}{4\pi R^3} = \left(\frac{3M}{4\pi V^3}\right) t^{-3}, \tag{1}$$

where t is the time from the beginning of expansion. All complications of the initial conditions—the high temperature, the neutrino burst, and the chemical composition—are absorbed into several input parameters of our models: M, V, and the energy available for the radioactive decays.

The temperature inside the expanding sphere varies because of several effects: adiabatic expansion, heat generation in radioactive decays, and radiative heat losses from the surface. Let us consider each of these effects.

Adiabatic expansion.—The density of the expanding envelope rapidly becomes very low, while the injection of a large amount of heat keeps it hot, and radiation energy density dominates the gas energy density. Therefore, we adopt

$$U = 3P = aT^4, \tag{2}$$

where U is the energy density, P is the pressure, T is the

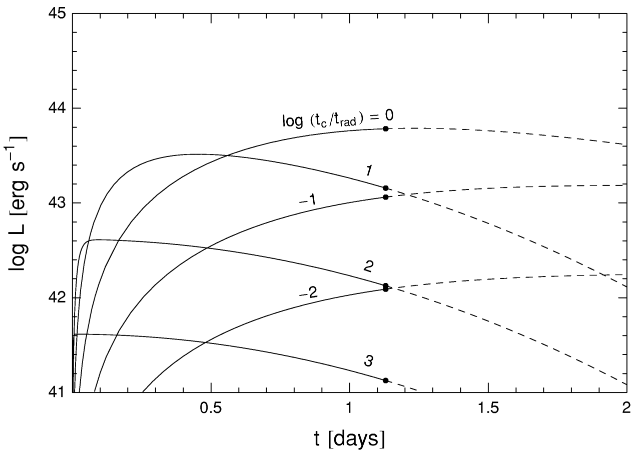

FIG. 1.—Time variation of the bolometric luminosity of the expanding sphere generated by a neutron star merger, shown for a number of models with various values of the logarithm of the ratio of two timescales t_c, when the sphere becomes optically thin, and the radioactive decay time $t_{\rm rad}$. The models were calculated for the fraction of rest-mass energy released in radioactive decay $f = 10^{-3}$, the mass $M = 10^{-2}\ M_\odot$, and the surface expansion velocity $V = 10^{10}$ cm s^{-1}. For the adopted opacity $\kappa = 0.2$ cm^2 g^{-1}, we have $t_c = 0.975 \times 10^5$ s = 1.13 days, as indicated by the filled circles, separating the solid lines (corresponding to the optically thick case) and the dashed lines (corresponding to the optically thin case).

temperature, and a is the radiation constant. Following the first law of thermodynamics, the variation of entropy S per unit mass is

$$T\,dS = \frac{1}{\rho}\ dU + \frac{4}{3}\ Ud\left(\frac{1}{\rho}\right) \approx \left(\frac{4\pi V^3}{3M}\right)\left(t^3\,dU + 4Ut^2\,dt\right). \quad (3)$$

Radioactive heating.—Assume that the radioactive decay of an element isotope proceeds on a timescale $t_{\rm rad}$, and releases a total amount of energy equivalent to a fraction f of the rest mass, so that the heat generation rate per gram per second is

$$\epsilon = \frac{fc^2}{t_{\rm rad}}\ \exp\left(\frac{-t}{t_{\rm rad}}\right). \quad (4)$$

If there are several decaying element isotopes, the total heat generation rate is the sum of the rates of the individual element isotopes. If there are many decaying element isotopes with different decaying timescales, the summation can be replaced by an integration. Nuclear lifetimes are distributed roughly uniformly in logarithmic intervals in time; thus, the total heat generation rate may be approximated as[1]

$$\epsilon = \frac{fc^2}{t}\ \text{ for } t_{\rm min} \le t \le t_{\rm max},\ t_{\rm min} \ll t_{\rm max}. \quad (5)$$

Radiative losses.—The temperature gradient is $\sim T/R$, the average opacity is $\kappa \approx \kappa_e \approx 0.2$ cm^2 g^{-1} (where κ_e is the opacity caused by electron scattering), and the radiative diffusion leads to heat losses from the surface that are approximately given by

$$F \equiv \sigma T_{\rm eff}^4 \approx \frac{\sigma T^4}{\kappa\rho R},$$

$$L = 4\pi R^2 F \approx \left(\frac{4\pi^2 V^4 c}{3\kappa M}\right) Ut^4, \quad (6)$$

where $\sigma = ac/4$ is the Stephan-Boltzmann constant and $T_{\rm eff}$ is the effective temperature. Throughout this Letter, we adopt the diffusion approximation, which requires the optical depth of the expanding sphere to be much larger than unity, i.e., $\kappa\rho R \gg 1$. The critical time t_c at which the expanding sphere becomes optically thin is given by $\kappa\rho R = 1$; thus,

$$t_c = \left(\frac{3\kappa M}{4\pi V^2}\right)^{1/2}$$

$$= 1.13\ \text{days}\ \left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{-1}\left(\frac{\kappa}{\kappa_e}\right)^{1/2}. \quad (7)$$

The overall heat balance is given by

$$L \approx \left(\epsilon - T\frac{dS}{dt}\right) M. \quad (8)$$

Combining equations (1)–(8), we obtain the equation for the variation of internal energy

$$t^3\frac{dU}{dt} + 4t^2 U \approx \left(\frac{3M}{4\pi V^3}\right)\epsilon - \left(\frac{\pi Vc}{\kappa M}\right) t^4 U. \quad (9)$$

3. SOLUTIONS OF THE MODEL

There are general properties of equation (9) that do not depend on the specific form of the radioactive energy generation term, $\epsilon(t)$. At the very beginning of expansion, at time on the order of a millisecond, the internal energy term U is likely to be very large. The initial evolution is well approximated by the adiabatic expansion, and both the radiative heat loss term ($\propto t^4 U$) and the heat generation term ($\propto \epsilon$) can be neglected.

The thermal evolution changes when the radioactive heat term becomes important, and it changes again when the radiative heat losses from the surface become important. However, the initial phase of adiabatic expansion makes the expanding sphere forget its initial thermal conditions. For this reason, in all the subsequent discussion of the analytical solution the initial conditions are found to be unimportant.

3.1. *Exponential-Law Decay*

The case of exponential-law decay, with $\epsilon(t)$ given by equation (4), is discussed in some detail in Li & Paczyński (1998). Analytical and numerical solutions of our simple model provide a consistent picture; for a given amount of radioactive energy, the transient event is the most luminous when $t_{\rm rad} \approx t_c$, and the peak luminosity is reached when the optical depth of the ejecta is of order unity.

The light curves are shown in Figure 1 for $M = 10^{-2}\ M_\odot$, $V = c/3$, $f = 10^{-3}$, $\kappa = 0.2$ cm^2 g^{-1} (thus $t_c \approx 0.975 \times 10^5$ s

[1] We are very grateful to D. N. Spergel, who suggested this formula to us.

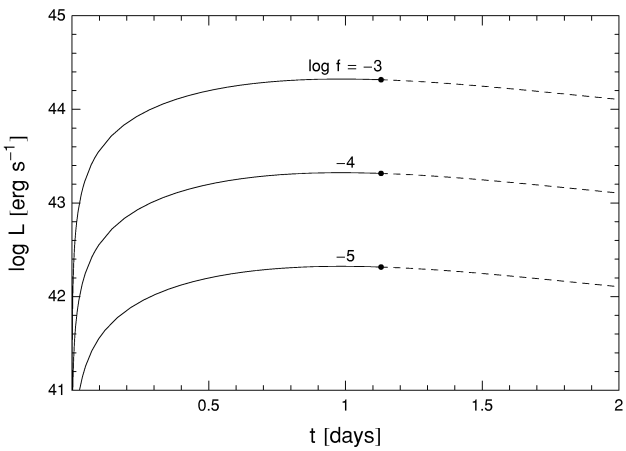

FIG. 2.—Time variation of the bolometric luminosity of the expanding sphere generated by a neutron star merger, shown for models with a large mix of radioactive nuclides, which provide a heating rate inversely proportional to time from the beginning of expansion. The models have three values of the fraction of rest mass released as heat: $f = 10^{-3}$, 10^{-4}, 10^{-5}, the mass $M = 10^{-2}\ M_\odot$, and the surface expansion velocity $V = 10^{10}$ cm s^{-1}. For the adopted opacity $\kappa = 0.2$ cm^2 g^{-1}, we have $t_c = 0.975 \times 10^5$ s $= 1.13$ days, as indicated with filled circles, separating the solid lines (corresponding to the optically thick case) and the dashed lines (corresponding to the optically thin case).

≈ 1.13 days), and $t_c/t_{\rm rad} = 10^3$, 10^2, 10, 1, 10^{-1}, and 10^{-2}, respectively. The initial condition is taken to be $T(t = 1\ {\rm ms}) = 2.8 \times 10^{10}$ K (but the results are insensitive to the initial conditions). The light curves are extended to the optically thin region by $L \approx \epsilon M$.

3.2. *Power-Law Decay*

The exponential-decay model was useful in demonstrating that very short and very long timescale radioactivity is inefficient for generating a large luminosity. The most efficient conversion of nuclear energy to the observable luminosity is provided by the elements with a decay timescale $t_{\rm rad}$ comparable to t_c, when the expanding sphere becomes optically thin. In reality, there is likely to be a large number of nuclides with a very broad range of decay timescales. Therefore, it is more realistic to adopt a power-law decay model, which automatically selects the most efficient radioactive timescales.

In the case of power-law decay with $\epsilon(t)$ given by equation (5), the analytic solution of equation (9) is

$$U = U_1\left[\frac{C}{\tau^4 e^{3\tau^2/8\beta}} + \sqrt{\frac{8\beta}{3}}\frac{1}{\tau^4}Y\left(\sqrt{\frac{3}{8\beta}}\,\tau\right)\right], \qquad (10)$$

where $U_1 = fMc^2/[(4\pi/3)\,V^3t_c^3]$, $\tau = t/t_c$, $\beta = V/c$, and the integration constant C is determined by the initial conditions. Dawson's integral Y is $Y(x) \equiv e^{-x^2}\int_0^x e^{s^2}\,ds$. In practice, the solution is insensitive to the initial conditions. With this approximation, we have $C \approx 0$. The corresponding luminosity is

$$L \approx L_0\sqrt{\frac{8\beta}{3}}Y\left(\sqrt{\frac{3}{8\beta}}\,\tau\right), \qquad (11)$$

where $L_0 = 3fMc^2/(4\beta t_c)$.

The time from the beginning of expansion to the peak luminosity is

$$t_m \approx 1.5\beta^{1/2}t_c$$
$$= 0.98\ {\rm days}\ \left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{-1/2}\left(\frac{\kappa}{\kappa_e}\right)^{1/2}. \qquad (12)$$

The peak luminosity is

$$L_m \approx 0.88\beta^{1/2}L_0 = 2.1 \times 10^{44}\ {\rm ergs\ s^{-1}}$$
$$\times \left(\frac{f}{0.001}\right)\left(\frac{M}{0.01\ M_\odot}\right)^{1/2}\left(\frac{3V}{c}\right)^{1/2}\left(\frac{\kappa}{\kappa_e}\right)^{-1/2}. \qquad (13)$$

The effective temperature at the peak luminosity is

$$T_{{\rm eff},\,m} \approx 0.79\beta^{-1/8}T_1 = 2.5 \times 10^4\ {\rm K}$$
$$\times \left(\frac{f}{0.001}\right)^{1/4}\left(\frac{M}{0.01\ M_\odot}\right)^{-1/8}\left(\frac{3V}{c}\right)^{-1/8}\left(\frac{\kappa}{\kappa_e}\right)^{-3/8}, \qquad (14)$$

where $T_1 = (U_1/a)^{1/4}$. From equation (11), the time at which the luminosity is down a factor of 3 from the peak luminosity is $t \approx 4.9\beta^{1/2}t_c$, which is in the optically thin regime for the subrelativistic case. For the optically thin case, the luminosity of the nonthermal radiation from the expanding shell is roughly given by $L \approx \epsilon M \approx (4/3)\,L_0\beta\tau^{-1}$, which is the asymptotic form of equation (11) for $\tau \gg \beta^{1/2}$. Thus, equation (11) can be formally extended to the optically thin region, where the radiation becomes nonthermal. The time from the peak luminosity to

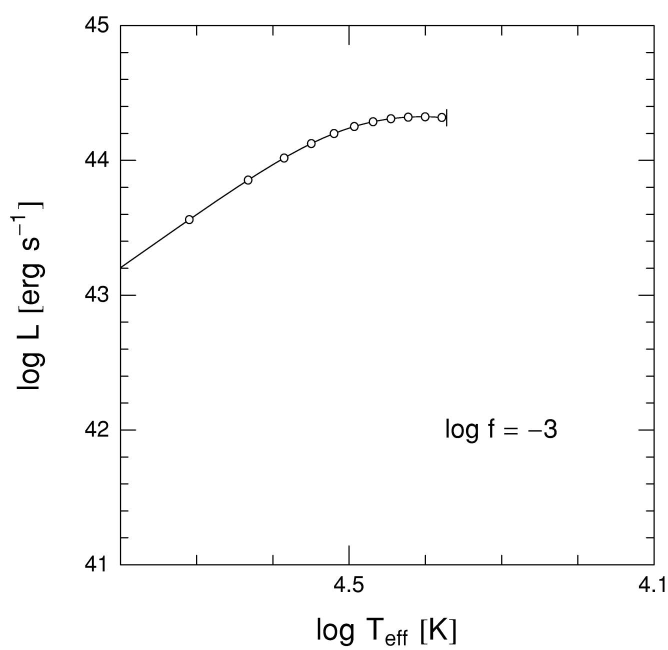

FIG. 3.—Evolution of the model from Fig. 2, with the fraction of rest-mass energy released in radioactive decay $f = 10^{-3}$. The evolution begins at a very small radius, with a very high $T_{\rm eff}$ and a very low L. The open circles correspond to the time of 0.1, 0.2, . . ., 1.1 days, and the vertical bar corresponds to the time $t_c = 0.975 \times 10^5$ s $= 1.13$ days, when the model becomes optically thin.

luminosity down by a factor of 3 from the peak is roughly

$$\Delta t \approx 3.4\beta^{1/2} t_c = 2.2 \text{ days} \times \left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{-1/2} \left(\frac{\kappa}{\kappa_e}\right)^{1/2}. \quad (15)$$

Figure 2 shows light curves drawn from equation (11), with $M = 10^{-2}\ M_\odot$, $V = c/3$, and $\kappa = 0.2\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, and $f = 10^{-3}$, 10^{-4}, and 10^{-5}, respectively. Figure 3 shows the evolution of the expanding shell in the log $T_{\rm eff}$–log L diagram for the case of $f = 10^{-3}$.

Note that the peak luminosity is proportional to f, while the shape of the light curve and all the timescales are independent of f (cf. eqs. [11]–[15]).

4. CONCLUSION

Our model is so simple that it can provide only an order-of-magnitude estimate of the peak luminosity and the timescale of the transient event that is likely to follow a violent merger of two neutron stars or a merger between a neutron star and a stellar-mass black hole. Equations (11)–(15) and Figures 2 and 3 provide a convenient representation of our model and show a simple relation between the poorly known input parameters—the mass of the ejecta M, their velocity V, and the fraction of rest-mass energy available for radioactive decays—and the observable parameters. Note that for a plausible set of input parameters, the transient reaches a peak luminosity of $L_m \approx 10^{44}$ ergs s^{-1}, corresponding to a bolometric luminosity of $M_{\rm bol} \approx -21$, i.e., in the bright supernova range. However, the duration of the luminous phase is likely to be only $t_m \approx 1$ day, i.e., much shorter than a supernova. The duration can be extended if the ejecta have a large mass and expand slowly (cf. eq. [12]).

While our model requires many improvements, the single most important is a quantitative estimate of the abundances and the lifetimes of the radioactive nuclides that form in the rapid decompression of nuclear-density matter. It is possible that Rosswog et al. (1998) may readily provide this improvement.

Because the frequency of such events is expected to be $\sim 10^3$ times lower than the supernova rate (Narayan et al. 1991; Phinney 1991; van den Heuvel & Lorimer 1996; Bloom et al. 1998), they may be detected soon in supernova searches. The merger events are likely to be hotter than supernovae, which could make them easier to detect at large redshifts. The dust extinction that affects some supernovae is not likely to be a problem, since the mergers are expected far from star-forming regions, many of them (perhaps most of them) outside parent galaxies (Tutukov & Yungelson 1994; Bloom et al. 1998; Zwart & Yungelson 1998). It is very intriguing that the high-redshift supernova search (Schmidt at al. 1998) revealed mysterious optical transients that typically have no host galaxy, as would be expected of neutron star mergers.

In principle, it should be fairly straightforward to test our suggestion by measuring future mystery events in four photometric bands and to determine three colors. In the optically thick phase, our model would follow a locus occupied by stars with more or less ordinary photospheres, evolving along a line corresponding to a fixed redshift and changing effective temperature. As soon as the expanding matter becomes optically thin, the colors would become nonstellar.

It is a great pleasure to thank D. N. Spergel for asking us the question "what might be the observable consequences of neutron star mergers?" and for his useful comments. One of us (B. P.) acknowledges hospitality he experienced while on sabbatical at the Institut d'Astrophysique, CNRS, in Paris.

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