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A TWO-COMPONENT EXPLOSION MODEL FOR THE GIANT FLARE AND RADIO AFTERGLOW FROM SGR 1806−20

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ABSTRACT

The brightest giant flare from the soft γ-ray repeater (SGR) 1806−20 was detected on 2004 December 27. The isotropic-equivalent energy release of this burst is at least 1 order of magnitude more energetic than those of the two other SGR giant flares. Starting from about 1 week after the burst, a very bright (∼80 mJy), fading radio afterglow was detected. Follow-up observations revealed the multifrequency light curves of the afterglow and the temporal evolution of the source size. Here we show that these observations can be understood in a two-component explosion model. In this model, one component is a relativistic collimated outflow responsible for the initial giant flare and the early afterglow, and the other component is a subrelativistic wider outflow responsible for the late afterglow. We also discuss the triggering mechanisms of these two components within the framework of the magnetar model.

Subject headings: gamma rays: bursts — ISM: jets and outflows — stars: individual (SGR 1806−20)

Online material: color figures

1. INTRODUCTION

Soft γ-ray repeaters (SGRs) emit short-duration (∼0.1 s) bursts of soft γ-rays and hard X-rays. They are believed to be magnetars, neutron stars with long periods of a few seconds and dipole fields of $\sim 10^{15}$ G (Thompson & Duncan 1995; Woods & Thompson 2005 for a recent review). Only three giant flares from SGRs have been detected so far, the brightest of which originated from SGR 1806−20 on 2004 December 27 (Hurley et al. 2005; Palmer et al. 2005; Mazets et al. 2005). The follow-up observations of the December 27 event revealed a bright radio afterglow with the size, proper motion, polarization, and flux at different radio frequencies all evolving with time (Gaensler et al. 2005; Cameron et al. 2005; Gelfand et al. 2005; Taylor et al. 2005). An obvious break in the multifrequency light curves of the afterglow occurred around day 9 after the burst, and subsequently the flux declined rapidly proportional to t^{α} (where $\alpha \sim -2.7$) between days 10 and 25. But the afterglow hardly faded during the period of days 25–33. In fact, it underwent a slower decay. The observed temporal evolution of the source size was $\theta(t) \propto t^{0.04\pm0.15}$ on days 7–10 (Cameron et al. 2005). This was followed by a faster increase (Taylor et al. 2005; also see Granot et al. 2005). The proper motion of the afterglow on days 7–17 was negligible but subsequently became significant (Taylor et al. 2005). In addition, the spectrum is generally consistent with a single–power-law index ($F_{\nu} \propto \nu^{\beta}$). Cameron et al. (2005) found $\beta = -0.62 \pm 0.02$ on day 7, and then the spectrum steepened from $\beta = -0.76 \pm 0.05$ on day 15 to $\beta = -0.9 \pm 0.1$.

Two different models have been proposed to explain these observational results. In Wang et al. (2005), we considered an initially relativistic energetic blast wave from the December 27 giant flare, following the suggestion that relativistic fireballs may occur in SGR bursts (Huang et al. 1998; Thompson & Duncan 2001). This is, in principle, the same mechanism established for gamma-ray burst afterglows (Mészáros & Rees 1997; Sari et al. 1998), i.e., the emission from a relativistically expanding blast wave that forms when the outflow from the SGR sweeps up the surrounding interstellar medium. To explain the light-curve break around day 9, we invoked a broken power-law distribution of the shock-accelerated electrons. This model appears to explain the rapid fading of the afterglow but cannot account for the rebrightening starting on day 25 and peaking on day 33.

Realizing this difficulty, some authors (Gaensler et al. 2005; Cameron et al. 2005; Gelfand et al. 2005; Granot et al. 2005) proposed a subrelativistic outflow model, in which the outflow from the giant flare initially expanded in a cavity at a constant velocity of $\sim 0.3c$ and, about 7 days later, happened to collide with a thin shell, which led to its deceleration by a reverse shock while the ambient matter was accelerated by a forward shock. In this model, the rapid decline of the afterglow flux was caused by adiabatic expansion of the reversely shocked electrons, and the rebrightening was due to initial coasting and subsequent deceleration of the outflow. This model predicts a size $\theta(t) \propto t$ in the coasting phase, which is inconsistent with the observations of Cameron et al. (2005). Furthermore, one has to assume an unobserved density bump igniting the fireball right before the observations started. It is unclear whether or not this could happen, and it is unclear as to what could be the source of the density bump.

The idea of an initially subrelativistic blast wave from SGRs was suggested by Cheng & Wang (2003), who explained the radio afterglow light curve of the 1998 August 27 giant flare from SGR 1900+14. For this event, a rebrightening could be seen, although the data were sparse (Frail et al. 1999). In this Letter, we propose a two-component explosion model to interpret the abundant observational data for the December 27 event. In this model, one relativistic collimated outflow is responsible for the initial giant flare and the early afterglow, and another subrelativistic wider outflow is responsible for the late afterglow. Our model seems to provide a unified picture in understanding the two giant flares and their radio afterglows from SGRs. In § 2, we discuss why two components are needed for the giant flares and radio afterglows, and in § 3, we fit the observed light curves at 4.86 and 8.46 GHz and the source size as a function of time. In § 4, we summarize our results.

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2. AN EXPLOSION WITH TWO COMPONENTS

Within the framework of the magnetar model, Thompson & Duncan (2001) proposed a triggering mechanism for giant flares, in which a helical distortion of the core magnetic field induces a large-scale cracking of the crust and a twisting deformation of the exterior magnetic field. This mechanism is consistent with the three observed timescales in the December 27 giant flare (Schwartz et al. 2005). It seems that the energy release for this mechanism includes two components. First, as the crust cracks, the exterior magnetic field deforms, which leads to a purely magnetohydrodynamic instability. Such an instability probably produces reconnection events and induces magnetohydrodynamic waves outside the star. The dissipated wave energy is initially locked onto the magnetic field in a thermal photon-pair plasma, which, under its own huge pressure, expands adiabatically along some surface magnetic lines and eventually drives a relativistic collimated outflow because of very low baryon loading. Second, when the core "toroidal" magnetic field floats up to break through the stellar crust, reconnection of the newborn surface magnetic field will drive an explosive outflow (Kluźniak & Ruderman 1998; Dai & Lu 1998). Because this magnetic field inevitably brings some crustal matter and because the reconnection occurs at about the stellar radius, the resultant outflow has high baryon contamination, and thus it is subrelativistic. Alternatively, even if only one exterior magnetic-reconnection event associated with the giant flare happens within the region whose size is less than the stellar radius above the surface (otherwise the energy release is too small to power the observed giant flare, because the dipole magnetic field steeply decreases with increasing radius, i.e., $B_d \propto R^{-3}$), the outward photon-pair flow launches a collimated outflow with very low baryon loading, as discussed above for a relativistic component. In the meantime, the inward emission impinges on the stellar surface, and its part is reflected back and reemitted from a larger solid angle, with much heavier baryon loading from the surface, as a subrelativistic component.

We now discuss why two components are needed to interpret the observational data. We consider a γ-ray energy release of the December 27 burst, $E_0 \sim 3 \times 10^{46}$ ergs, near the surface of a magnetar with a radius of $R_0 \sim 10^6$ cm in a time of $t_0 \sim 0.2$ s, and thus the outflow luminosity is at least $L_0 \sim 10^{47}$ ergs s^{-1}, as implied by the observed hard spike (Hurley et al. 2005). An extremely large optical depth means a radiation-pair outflow with an initial temperature of

$$T_0 = \left(\frac{L_0}{16\pi R_0^2 \sigma}\right)^{1/4} = 210 L_{0,47}^{1/4} R_{0,6}^{-1/2}\ \mathrm{keV}, \qquad (1)$$

where $L_{0,47} = L_0/10^{47}$ ergs s^{-1}, $R_{0,6} = R_0/10^6$ cm, and σ is the Stephan-Boltzmann constant. Assuming the baryon-loading rate of the outflow, $\dot{M}$, we define a dimensionless entropy $\eta = L_0/\dot{M}c^2$.

If $\eta > 1$, this outflow will expand relativistically as the Lorentz factor $\Gamma \propto R$ and the temperature $T \propto R^{-1}$ (Shemi & Piran 1990). The temperature, Lorentz factor, and radiation luminosity at the photosphere become $\Gamma_f = \min[\eta, \eta_*]$, $T_{\rm ph} = T_0 \min[(\eta/\eta_*)^{8/3}, 1]$, and $L_{\rm ph} = L_0 \min[(\eta/\eta_*)^{8/3}, 1]$ respectively, where $\eta_* = [L_0 \sigma_{\rm T}/(4\pi m_p c^3 R_0)]^{1/4} \simeq 100 L_{0,47}^{1/4} R_{0,6}^{-1/4}$ (Mészáros & Rees 2000). As suggested by Nakar et al. (2005) and Ioka et al. (2005), the giant flare might have arisen from the emission at the photosphere and/or internal shocks if the outflow is variable. The observed average temperature of the hard spike, $T_{\rm spike} = 175 \pm 25$ keV (Hurley et al. 2005), requires $\eta = 93 L_{0,47}^{5/32} R_{0,6}^{-1/16}$.

If $\eta < 1$, the outflow will also expand under its own pressure, which includes the gas pressure and radiation pressure, $P = P_g + P_r = n_p k_{\rm B} T + 4\sigma T^4/(3c)$, where $n_p = \dot{M}/(4\pi R^2 m_p c)$ is the proton number density at radius R. Letting $P_g = P_r$ at radius R_0, we define the critical baryon-loading rate, $\dot{M}_{\rm cr} = 16\pi\sigma m_p R_0^2 T_0^3/(3k_{\rm B}) = 1.7 \times 10^{29} L_{0,47}^{3/4} R_{0,6}^{1/2}$ g s^{-1}. If the baryon-loading rate is below $\dot{M}_{\rm cr}$, the radiation pressure exceeds the gas pressure so that the temperature decays $T \propto R^{-1}$. In this case, the temperature and radiation luminosity at the photosphere decrease to

$$T_{\rm ph} = T_0 R_0/R_{\rm ph} = 220 L_{0,47}^{1/4} R_{0,6}^{1/2} \dot{M}_{25}^{-1}\ \mathrm{K} \qquad (2)$$

and

$$L_{\rm ph} = 4\pi R_{\rm ph}^2 \sigma T_{\rm ph}^4 = 2.0 \times 10^{32} L_{0,47} R_{0,6}^2 \dot{M}_{25}^{-2}\ \mathrm{ergs\ s^{-1}}, \qquad (3)$$

where the photospheric radius $R_{\rm ph} = \sigma_{\rm T} \dot{M}/(4\pi m_p c) = 1.1 \times 10^{13} \dot{M}_{25}$ cm with $\dot{M}_{25} = \dot{M}/10^{25}$ g s^{-1}. However, if the baryon-loading rate exceeds $\dot{M}_{\rm cr}$, the gas pressure dominates over the radiative pressure, and the temperature decays as $T \propto R^{-2}$. In this case, the temperature and radiation luminosity at the photosphere are

$$T_{\rm ph} = T_0 (R_0/R_{\rm ph})^2 = 2.0 \times 10^{-5} L_{0,47}^{1/4} R_{0,6}^{3/2} \dot{M}_{25}^{-2}\ \mathrm{K} \qquad (4)$$

and

$$L_{\rm ph} = 1.4 \times 10^4 L_{0,47} R_{0,6}^6 \dot{M}_{25}^{-6}\ \mathrm{ergs\ s^{-1}}. \qquad (5)$$

Thus, the temperature and luminosity of the emission from the subrelativistic outflow at the photosphere in both cases are much less than those of the giant flare, showing that a subrelativistic outflow model for explaining the giant flare can be ruled out.

Therefore, we conclude that an ultrarelativistic outflow is required by the extremely high peak luminosity with millions of the Eddington value, hard spectrum, and rapid variability of the initial spike emission of the giant flares. Furthermore, a relativistic jet model indeed provides a satisfactory explanation for the observed light curve of the initial spike of the December 27 giant flare, as shown by Yamazaki et al. (2005). It is possible that such an outflow, after emitting the hard spike, retains some amount of energy and then drives a blast wave when sweeping into the ambient medium.

On the other hand, an obvious bump at $t_{\rm dec} \sim 30$ days in the 4.86 GHz light curve of the radio afterglow for the December 27 event and a possible bump at $t_{\rm dec} \sim 10$ days for the August 27 event imply that subrelativistic outflows with initial velocities of $\beta_{\rm nr,0} c$ could begin to be decelerated by the ambient medium with density of n at $t_{\rm dec}$. Thus, we obtain the outflow mass and kinetic energy

$$M_{\rm nr} = 1.2 \times 10^{24} \beta_{\rm nr,0}^3 n_{-2} (t_{\rm dec}/10\ \mathrm{days})^3\ \mathrm{g} \qquad (6)$$

and

$$E_{\rm nr} = 5.4 \times 10^{44} \beta_{\rm nr,0}^5 n_{-2} (t_{\rm dec}/10\ \mathrm{days})^3\ \mathrm{ergs}, \qquad (7)$$

where $n_{-2} = n/10^{-2}$ cm^{-3}. This outflow could also drive a forward shock with negligible energy loss.

In short, there could have been two blast waves after the December 27 giant flare. In the following we show that an

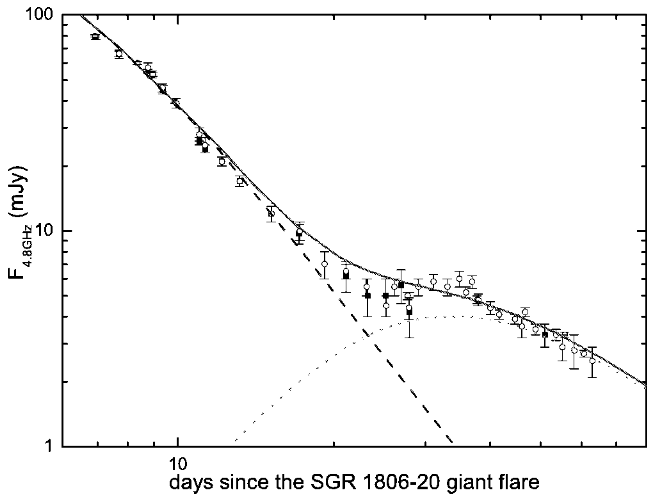

FIG. 1.—Modeling the 4.86 GHz afterglow of the December 27 giant flare from SGR 1806−20 in the two-component explosion model. The physical parameter values are given in the text. The dashed and dotted lines represent the contributions from the initially ultrarelativistic and subrelativistic components, respectively, while the solid line is the sum of both contributions. The data are taken from Gelfand et al. (2005; *open circles*) and Cameron et al. (2005; *filled squares*). [*See the electronic edition of the Journal for a color version of this figure.*]

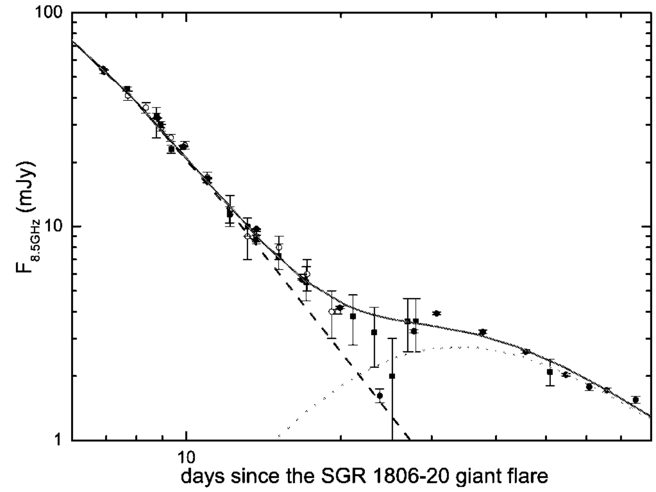

FIG. 2.—Modeling the 8.46 GHz afterglow of the December 27 giant flare from SGR 1806−20 in the two-component explosion model with the same parameter values as in Fig. 1. The data are taken from Cameron et al. (2005; *filled squares*), Gaensler et al. (2005; *open circles*), and Taylor et al. (2005; *filled circles*) [*See the electronic edition of the Journal for a color version of this figure.*].

initially relativistic shock is responsible for the early afterglow, and a nonrelativistic shock for the late afterglow.

3. FITTING THE AFTERGLOW LIGHT CURVE AND SIZE

We consider two energetic shocks after the December 27 giant flare: one initially ultrarelativistic blast wave with an opening angle of θ_j, an isotropic-equivalent energy of E_r, and a Lorentz factor $\Gamma_0 \gg 1$, and another subrelativistic forward shock with an energy of $E_{\rm nr}$ and an initial velocity of $\sim 0.2c$. Both shocks expand in a uniform medium with density of n. The initially relativistic blast wave will enter the nonrelativistic phase at $t_{\rm nr} = 4.0E_{r,44}^{1/3}n_{-2}^{-1/3}$ days and is expected to play a dominant role in the early radio afterglow, where $E_{r,44} = E_r/10^{44}$ ergs. As suggested in Wang et al. (2005), the electron energy distribution in this blast wave is taken to be a broken power-law form with p_1 and p_2 below and above the break Lorentz factor γ_b during the trans-relativistic stage,

$$\frac{dN_e}{d\gamma_e} \propto \begin{cases} \gamma_e^{-p_1}, & \text{if } \gamma_{\min} \le \gamma_e < \gamma_b, \\ \gamma_e^{-p_2}, & \text{if } \gamma_e \ge \gamma_b, \end{cases} \qquad (8)$$

where $\gamma_{\min}$ is the minimum Lorentz factor. Observationally, such an electron distribution is not only required by the spectral evolution of the afterglow (Cameron et al. 2005) and the synchrotron spectrum of the Crab Nebula (Amato et al. 2000) but also suggested in fitting two gamma-ray burst afterglows (Li & Chevalier 2001) and TeV blazars (Tavecchio et al. 1998). Theoretically, the recent particle simulation of a relativistic two-stream instability by Dieckmann (2005) revealed a broken power-law distribution. Wang et al. (2005) have shown that this distribution can account for the frequency-dependent breaks of the light curves around day 9 and the steepening of the radio-band spectra with time (Cameron et al. 2005).

The initially subrelativistic component may largely contribute to the radio afterglow emission only at late times, as it is decelerated and the swept-up matter accumulates. According to this scenario, the observed bump time $t \sim 30$ days corresponds to the deceleration time $t_{\rm dec}$ of this component, so we infer $\beta_{\rm nr,0} = R_{\rm nr}/ct_{\rm dec} = 0.38(R_{\rm nr}/3\times10^{16}\ {\rm cm})(t_{\rm dec}/30\ {\rm days})^{-1}$, where $\beta_{\rm nr,0}$ is the initial velocity of the subrelativistic component and $R_{\rm nr}$ is the blast wave radius at the bump time. Then we can constrain the isotropic-equivalent energy of this component from the deceleration time, i.e., $E_{\rm nr} = 1.5\times10^{44}n_{-2}(t_{\rm dec}/30\ {\rm days})^3 \times (\beta_{\rm nr,0}/0.4)^5$ ergs (from eq. [7]). The electron energy distribution for this component is assumed to be a single–power-law one with index p. This is deduced from the spectrum form of the late radio afterglow of the 1998 August 27 giant flare from SGR 1900+14.

We first carried out numerical calculations of the dynamics of each blast wave without lateral spreading based on Huang et al. (2000) and obtained the temporal evolution of the source's radius. We next calculated light curves of the synchrotron radiation from the shocked matter at different frequencies, assuming that the electron energy distribution has the same form as equation (8) and that ϵ_e and ϵ_B are fractions of the total energy density that go into the electrons and magnetic field, respectively. Combining the contributions from both components, we performed a numerical fitting to the light curves at 4.86 and 8.46 GHz in Figures 1 and 2, respectively. In the fitting, the physical parameter values are taken: $\Gamma_0 = 100$, $E_r = 2.3\times10^{45}$ ergs, $\theta_j = 0.129$, $p_1 = 2.2$, $p_2 = 3.5$, and $R_b \equiv \gamma_b/\gamma_{\min} = 20$ for the initially relativistic component and $E_{\rm nr} = 0.75\times10^{44}$ ergs, $\Gamma_{\rm nr,0} = 1.023$, and $p = 2.4$ for the initially subrelativistic component. The other parameter values are $n = 0.0363\ {\rm cm}^{-3}$, $\epsilon_e = 0.34$, and $\epsilon_B = 0.23$. We take the distance to the source,[3] $d = 9.8$ kpc (Cameron et al. 2005), which is slightly less than used in previous works. Our fitting gives the total $\chi^2/{\rm dof} = 374/(79-11) = 5.5$ for 11 physical parameters.

The evolution of the source size with time was reported for the December 27 event (Gaensler et al. 2005; Cameron et al. 2005; Granot et al. 2005; Taylor et al. 2005). For the two-component model, the measured size at any time should be dominated by the brighter component. In Figure 3, we present the evolution of the source sizes of the initially relativistic and subrelativistic components, denoted by the dashed and dotted lines, respectively. From the light curves in Figure 2, we see that the flux density of the initially subrelativistic component

[3] For $d = 15$ kpc (Corbel & Eikenberry 2004), we have also fitted the light curves of the radio afterglow and the source size.

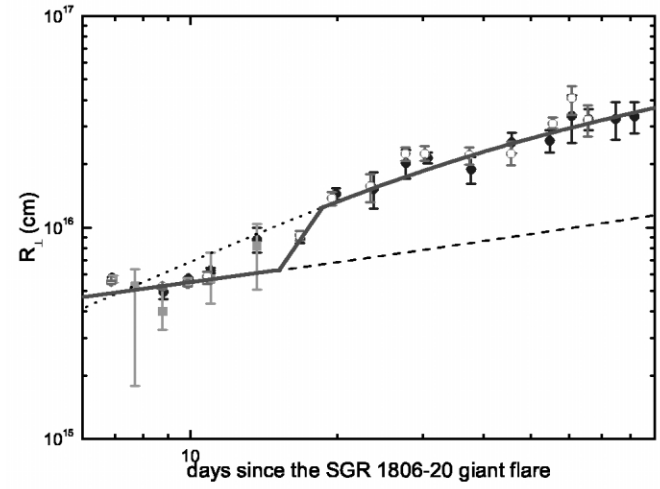

FIG. 3.—Modeling the size evolution of the radio afterglow of the 2004 December 27 giant flare from SGR 1806−20 in the two-component model with the same parameter values as Fig. 1. The dashed and dotted lines represent the size evolution of the initially ultrarelativistic and subrelativistic components, respectively. The solid line is the size of the brighter of the two components. The data are taken from Cameron et al. (2005; *filled squares*), Granot et al. (2005; *open circles*), and Taylor et al. (2005; *filled circles*). [*See the electronic edition of the Journal for a color version of this figure.*]

begins to dominate over that of the initially relativistic component around day 20, so that the measured sizes should be the sizes of the initially relativistic and subrelativistic components before and after this time, respectively. The solid line linking both components in Figure 3 indicates the transition regime between the two phases.

4. CONCLUSIONS

We have proposed a two-component explosion model, in which one initially relativistic collimated outflow can account for the spectrum of the giant flare and the early-time broken light curves at different radio frequencies and the slow increase of the source size, and another subrelativistic wider outflow for the late-time rebrightening of the radio afterglow and the faster increase of the source size. In addition, our model is consistent with the magnetar scenario (Thompson & Duncan 2001; also see Cea 2005). In this scenario, two magnetic reconnection events may happen near the surface and in the magnetosphere, respectively, which give rise to a relativistic collimated outflow and a subrelativistic outflow because of different baryon loadings. Alternatively, even if only one magnetic reconnection event associated with the giant flare happens within a small region above the surface, the outward photon-pair flow launches a relativistic collimated fireball while the inward flow strikes the surface and is partially reemitted as a subrelativistic baryonic outflow from a larger solid angle. Finally, the relativistic component from a giant flare like the December 27 event may be diagnosed using future high-energy data, as noted by Fan et al. (2005).

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