A TWO-COMPONENT EXPLOSION MODEL FOR THE GIANT FLARE
AND RADIO AFTERGLOW FROM SGR1806-20

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Draft version March 2, 2022

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 one order of magnitude more energetic than those of the two SGR giant flares. Starting from about one week after the burst, a very bright (∼ 80 mJy), fading radio afterglow was detected. Follow-up observations revealed the multi-frequency 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 another component is a subrelativistic wider outflow responsible for the late afterglow. We also discuss 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)

1. INTRODUCTION

Soft γ-ray repeaters (SGRs) emit short-duration (∼ 0.1 seconds) bursts of soft γ- and hard X-rays. They are believed to be magnetars, neutron stars with long periods of a few seconds and dipole fields of ∼ 1015 Gauss (Thompson & Duncan 1995; Woods & Thompson 2004 for a recent review). Only three giant flares from SGRs have been detected so far, the brightest of which originated from SGR1806-20 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; Granot et al. 2005). An obvious break in the multi-frequency light curves of the afterglow occurred around day 9 after the burst and subsequently the flux declined rapidly as ∝ t−α (where α ∼ −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 θ(t) ∝ t−0.04±0.15 on days 7 to 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 (Fν ∝ νβ). Cameron et al. (2005) found β = −0.62 ± 0.02 on day 7 and then the spectrum steepened from β = −0.76 ± 0.05 on day 15 to β = −0.9 ± 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, Dai & Lu 1998; Thompson & Duncan 2001). This is, in principle, the same mechanism established for GRB afterglows (Mészáros & Rees 1997; Sari, Piran & Narayan 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 ∼ 0.3c and about 7 days later it 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 coastaling and subsequent deceleration of the outflow. This model predicts a size θ(t) ∝ 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 to ignite the fireball right before the observations started. It is unclear whether this could happen and 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 SGR1900+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 GHz and 8.46 GHz and the source size as a function of time. In §4, we summarize our results.

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 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 re-emitted 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 $\gamma$-ray energy release of the December 27 burst, $E_0 \sim 3 \times 10^{46}$ ergs, near the surface of a magnetar with 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 $L_0 \sim 10^{47}$ erg 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

$$T_0 = \left( \frac{L_0}{16\pi R_0^2 \sigma} \right)^{1/4} = 210 L_{0.47}^{1/4} R_{0.6}^{-1/2} \text{keV},$$

where $L_{0.47} = L_0/10^{47}$ erg s$^{-1}$, $R_{0.6} = R_0/10^6$ cm, and $\sigma$ 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 $\Gamma_t = \min[\eta, \eta_s]$, $T_{ph} = T_0 \times \min[\eta, \eta_s]^{8/3}$, and $L_{ph} = L_0 \times \min[\eta, \eta_s]^{8/3}$, respectively, where $\eta_s = [L_0\sigma T/(4\pi m_p c^3 R_0)]^{1/4} \approx 100 L_{0.47}^{1/4} R_0^{-1/14}$ (Mészáros & Rees 2000). As suggested by Nakar, Piran & Sari (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 variable. The observed average temperature of the hard spike, $T_{spike} = 175 \pm 25$ keV (Hurley et al. 2005), requires $\eta = 93 L_{0.47}^{5/3} R_0^{-1/16}$.

If $\eta < 1$, the outflow will also expand under its own pressure, which includes the gas pressure and radiation pressure, $P = P_g + P_r = n_p k_B T + 4\pi T^4/(3c^2)$, where $n_p = M/(4\pi R^2 m_p c)$ is the proton number density at radius $R$. Letting $P_g = P_r$ at radius $R_0$, we define the critical baryon loading rate, $M_{cr} = 16 \pi m_p R_0^2 T_0^4/(3k_B) = 1.7 \times 10^{29} L_{0.47}^{3/4} R_{0.6}^{-2}$ g s$^{-1}$. If the baryon loading rate is below $M_{cr}$, 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 decreases to

$$T_{ph} = T_0 R_0/R_{ph} = 220 L_{0.47}^{1/4} R_{0.6}^{1/2} M_{25}^{-1} \text{K},$$

and

$$L_{ph} = 4\pi R_{ph}^2 \sigma T_{ph}^4 = 2.0 \times 10^{32} L_{0.47} R_{0.6}^2 M_{25}^{-2} \text{erg s}^{-1},$$

where the photospheric radius $R_{ph} = \sigma T M/(4\pi m_p c) = 1.1 \times 10^{13} M_{25}$ cm with $M_{25} = M/10^{25}$ g s$^{-1}$. However, if the baryon loading rate exceeds $M_{cr}$, 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

$$T_{ph} = T_0 (R_0/R_{ph})^2 = 2.0 \times 10^{-5} L_{0.47}^{1/4} R_{0.6}^{3/2} M_{25}^{-2} \text{K},$$

and

$$L_{ph} = 1.4 \times 10^4 L_{0.47} R_{0.6}^6 M_{25}^{-6} \text{erg s}^{-1}.$$

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

$$M_{nr} = 1.2 \times 10^{24} \beta_{nr,0}^3 n^{-2} (t_{\text{dec}}/10 \text{ days})^3 \text{ g}, \quad (6)$$

and

$$E_{nr} = 5.4 \times 10^{44} \beta_{nr,0}^5 n^{-2} (t_{\text{dec}}/10 \text{ days})^3 \text{ ergs}, \quad (7)$$

where $n^{-2} = n/10^{-2} \text{ cm}^{-3}$. 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 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 $\theta_j$, an isotropic-equivalent energy of $E_r$, and the Lorentz factor $\Gamma_0 \gg 1$, and another subrelativistic forward shock with an energy of $E_{nr}$ 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 non-relativistic phase at $t_{nr} = 4.0E_{nr,44}^{-1/3} n^{-2/3} \text{ days}$, and it is expected to play a dominant role in the early radio afterglow, where $E_{nr,44} = E_{nr}/10^{44}\text{ ergs}$. As suggested in Wang et al. (2005), the electron energy distribution in this blast wave is taken to be a broken power-law form $\gamma > 1$ and $\gamma > b$ below and above the break Lorentz factor $\gamma_b$ during the trans-relativistic stage,

$$\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p_1}, \quad \text{if} \quad \gamma_{\text{min}} \leq \gamma_e < \gamma_b,$$

$$\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p_2}, \quad \text{if} \quad \gamma_e \geq \gamma_b, \quad (8)$$

where $\gamma_{\text{min}}$ 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, Maraschi & Ghisellini 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 sub-relativistic 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 $t_{\text{dec}}$ of this component, so we infer $\beta_{nr,0} = R_{nr}/ct_{\text{dec}} = 0.38[R_{nr}/3 \times 10^{50}\text{ cm}](t_{\text{dec}}/30 \text{ d})^{-1}$, where $\beta_{nr,0}$ is the initial velocity of the sub-relativistic component and $R_{nr}$ 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.,

$$E_{nr} = 1.5 \times 10^{44} n^{-2} (t_{\text{dec}}/30 \text{ d})^3 \beta_{nr,0}^{3.5} (0.4)^{5} \text{ ergs} \quad \text{(from equation 7).}$$

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 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 $\epsilon_e$ and $\epsilon_B$ are fractions of the total energy density that go into the electrons and magnetic field respectively. Combining the contributions from both components, we performed numerical fitting to the light curves at 4.86 GHz and 8.46 GHz in Figures 1 and 2 respectively. In the fitting, the physical parameter values are taken: $\Gamma_0 = 100$, $E_r = 2.3 \times 10^{42} \text{ ergs}$, $\theta_j = 0.129$, $p_1 = 2.2$, $p_2 = 3.5$, and $R_0 = \gamma_b / \gamma_{\text{min}} = 20$ for the initially relativistic component, and $E_{nr} = 0.75 \times 10^{44} \text{ ergs}$, $\Gamma_{nr,0} = 1.023$, and $p = 2.4$ for the initially subrelativistic component. The other parameter values are $n = 0.0363 \text{ cm}^{-3}$, $\epsilon_e = 0.34$, and $\epsilon_B = 0.23$. We take the distance to the source, $d = 9.8 \text{ kpc}$ (Cameron et al. 2005), which is slightly less than used in previous works. Our fitting gives the total $\chi^2/dof = 374/(79 - 11) = 5.5$ 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 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 of Thompson & Duncan (2001). 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 re-emitted 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, Zhang & Wei (2005).

We thank the referee for valuable comments. This work was supported by the Ministry of Science and Technology of China (NKBRSF G19990754), the Special Funds for Major State Basic Research Projects, the FANEDD 200125, and the National Natural Science Foundation of China under grants 10403002, 10233010 and 10221001. B. Zhang was supported by NASA NNG04GD51G and a NASA Swift GI (Cycle 1) program.

REFERENCES

Amato, E. et al. 2000, A&A 359, 1107
Cameron, P. B. et al. 2005, Nature, 434, 1112
Cheng, K. S., & Wang, X. Y. 2003, ApJ, 593, L85
Dai, Z. G., & Lu, T. 1998, Phys. Rev. Lett., 81, 4301
Dieckmann, M. E. 2005, Phys. Rev. Lett., 94, 155001
Fan, Y. Z., Zhang, B., & Wei, D. M. 2005, MNRAS, in press (astro-ph/0505483)
Frail, D., Kulkarni, S. R., & Bloom, J. 1999, Nature, 398, 127
Gaensler, B. M. et al. 2005, Nature, 434, 1104
Gelfand, J. D. et al. 2005, ApJ, submitted (astro-ph/0503269)
Granot, J. et al. 2005, ApJ, submitted (astro-ph/0503251)
Huang, Y. F., Dai, Z. G., & Lu, T. 1998, Chinese Phys. Lett., 15, 775
Huang, Y. F., Gou, L. J., Dai, Z. G., & Lu, T. 2000, ApJ, 543, 90
Hurley, K. et al. 2005, Nature, 434, 1098
Ioka, K., Razzaque, S., Kobayashi, S., & Mészáros, P. 2005, astro-ph/0503279
Kluźniak, W., & Ruderman, M. 1998, ApJ, 505, L113
Li, Z.-Y., & Chevalier, R. A. 2001, ApJ, 551, 940
Mazets, E. P. et al. 2005, astro-ph/0502541
Mészáros, P., & Rees, M. J. 1997, ApJ, 476, 232
Mészáros, P., & Rees, M. J. 2000, ApJ, 530, 292
Nakar, E., Piran, T., & Sari, R. 2005, astro-ph/0502052
Palmer, D. M. et al. 2005, Nature, 434, 1107
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Schwartz, S. J. et al. 2005, ApJ, in press (astro-ph/0504056)
Shemi, A., & Piran, T. 1990, ApJ, 365, L55
Tavecchio, F., Maraschi, L., & Ghisellini, G. 1998, ApJ, 509, 608
Taylor, G. B. et al. 2005, ApJ, submitted (astro-ph/0504363)
Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255
Thompson, C., & Duncan, R. C. 2001, ApJ, 561, 986
Wang, X. Y., Wu, X. F., Fan, Y. Z., Dai, Z. G., & Zhang, B. 2005, ApJ, 623, L29
Woods, P. M., & Thompson, C. 2005, To appear in “Compact Stellar X-ray Sources”, eds. W.H.G. Lewin and M. van der Klis, astro-ph/0406133
Yamazaki, R., Ioka, K., Takahara, F., & Shibazaki, N. 2005, astro-ph/0502320
Fig. 1.— Modelling 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, solid squares).
Fig. 2.— Modelling 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 Figure 1. The data are taken from Cameron et al. (2005, solid squares), Gaensler et al. (2005, open circles) and Taylor et al. (2005, solid circles).
Fig. 3.— Modelling 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 Figure 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 one between both components. The data are taken from Cameron et al. (2005, solid squares), Granot et al. (2005, open circles), and Taylor et al. (2005, solid circles).