

Giant Flare of SGR 1806-20 from a Relativistic Jet

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(Received 2005 March 0; accepted 2005 0)

Abstract

Japanese magnetospheric explorer GEOTAIL recorded a detailed light curve during the initial 600 msec of a giant flare from SGR 1806-20 on December 27, 2004. We show that the observed light curve is well explained by an emission from relativistically expanding fireballs, like those of gamma-ray bursts (GRBs). Especially, the observed rapid fading after 500 msec suggests that ejecta is collimated in a jet. We derive an upper limit on the jet opening half-angle of 0.2 radian that is as narrow as those of GRBs.

Key words: gamma rays: theory — stars: neutron — stars: pulsars: individual (SGR 1806-20) — ISM: jets and outflows

1. Introduction

Soft gamma-ray repeaters (SGRs) are most likely highly magnetized neutron stars, so called magnetars (Thompson & Duncan 1995). On December 27, 2004, a giant flare from SGR 1806-20 illuminated the Earth (Boggs et al. 2004; Hurley et al. 2005; Palmer et al. 2005) with the gamma-ray flux more than $\sim 10^6$ times that of the typical cosmological gamma-ray bursts (GRBs) that are the most violent explosions in the universe. The giant flare has an initial spike lasting about 600 msec with an isotropic equivalent energy of $\sim 10^{46-47}$ ergs, that is followed by a pulsating tail lasting 400 seconds with energy of $\sim 10^{44}$ ergs. Only two giant flares from SGRs had been recorded before this flare: they occurred on March 5, 1979 from SGR 0526-66 (Cline et al. 1980) and August 27, 1998 from SGR 1900-14 (Hurley et al. 1999), respectively. The initial spike of the most recent flare is $\sim 10^2$ times more energetic than the previous two events, while pulsating tails of the three events have comparable energies (e.g., Woods 2004).

Because of the observed high flux density, most γ -ray detectors were saturated except for particle detectors such as GEOTAIL that successfully recorded a burst light curve in the brightest initial spike (Terasawa et al. 2005; see also Mazets et al. 2005). The burst was so bright that the light curve was clearly recorded down to three orders of magnitude below the peak flux. In the early epoch ($t < 160$ msec), the light curve is variable and mainly consists of two pulses. A gradual power-law like decay begins after the second peak ($t > 160$ msec) with a bump at $t \sim 430$ msec. This is followed by a rapid fading after $t \sim 500$ msec. Such a detailed light curve of the initial spike has been measured for the first time. It brings us a new key to understanding of the mysterious, poorly un-

derstood SGRs.

The detection of radio afterglows after giant flares suggests that SGRs eject relativistic outflows (Cameron et al. 2005; Gaensler et al. 2005; Frail, Kulkarni & Bloom 1999). A relativistic motion is also implied by the nonthermal flare spectrum observed by Mazets et al. (2005) and Palmer et al. (2005), otherwise pair formation occurs in a compact emission region, which makes thermal spectrum (Huang, Dai & Lu 1998; Thompson & Duncan 2001; Nakar, Piran & Sari 2005). Even if the spectrum is thermal (Hurley et al. 2005), its hyper-Eddington luminosity implies a relativistic motion (Wang et al. 2005). The initial spike and the pulsating tail have different spectral features and temporal pulse profiles, which suggests that they have different origins: the initial spike and the radio afterglow may arise from the relativistic outflow, and the pulsating tail may come from evaporating trapped fireballs. The kinetic energy of the outflow inferred from the radio afterglow is $\sim 10^{44-45}$ ergs (Cameron et al. 2005; Gaensler et al. 2005), which is much smaller than the isotropic equivalent energy of the initial γ -ray spike. Hence a collimated relativistic outflow is implied. In addition the isotropic equivalent energy of the initial spike is comparable to that of the exterior magnetic field $B \sim 10^{15}$ G of the magnetar. Then the magnetar cannot produce giant flares repeatedly (e.g., ~ 100 times) during its active time ($\sim 10^4$ yrs) unless the emission is collimated or there is other energy reservoir. Therefore we have fair motivations to consider an anisotropic giant flare.

If the giant flares of SGRs arise from relativistic collimated outflows, they are similar to canonical GRBs from the cosmological distance (typically tens of Gpc). A sub-group of GRBs with long duration is thought to be caused by relativistic jets that originate in the collapse of a massive star (Hjorth et al. 2003; Stanek et

al. 2003). Energy is carried away from a compact source as kinetic energy of jets (Piran 1999; Piran 2004; Zhang & Mészáros 2004). This is converted into radiation by internal shocks between shells, which make observed highly variable gamma-ray light curves, called prompt emissions of GRBs. Subsequently, at larger radii, outflow interacts with ambient circumstellar matter, producing external shocks, which are responsible for afterglows on much longer time scales in various wave lengths, such as radio, optical, and X-ray bands.

In this Letter, we show that the observed light curve of the initial 600 msec is well explained by the emission from relativistically expanding fireballs, like those of GRBs. Especially, the observed rapid fading after 500 msec suggests that ejecta is collimated in a jet. We derive a robust upper limit on the jet opening half-angle of 0.2 radian that is as narrow as those of GRBs.

2. Light curve of collimated outflow

The light curve of the initial spike of the giant flare from SGR 1806-20 is very similar to the behavior in prompt GRB emissions (see Figure 1). We can interpret two pulses in the early epoch ($t < 160$ msec) as two internal shocks (see below). The following decay is basically determined by the relativistic kinematics, which is independent of the emission mechanism. Suppose a relativistic shell shines for a short period. Since the shell has a curvature, photons far from the line of sight (LOS) come later. The shell at higher latitude from the LOS has a lower velocity toward the observer, so that the emission becomes dimmer and softer as time goes because of the relativistic Doppler effect, which explains the observed power-law like decay during between 200 and 400 msec very well. If the emission is spherical (isotropic), however, such a decay should continue beyond $t \gtrsim 600$ msec. This is inconsistent with the observation that the light curve rapidly fades after $t \sim 600$ msec, which implies that the emission does not occur at larger angle from the LOS. In other words, the giant flare arises from a relativistic jet with a finite opening angle.

In order to see the above arguments quantitatively, we consider a simple model for emission from a relativistically moving jet which radiates photons when the shell is located at radius from r_0 to r_e (Yamazaki, Ioka & Nakamura 2003). We assume that the cooling timescale is much shorter than other timescales, and hence consider an instantaneous emission at the shock front. We use a spherical coordinate system (t, r, θ, ϕ) in the Lab frame, where the $\theta = 0$ axis points toward the detector at $r = D$, and the magnetar is located at $r = 0$. The jet has an opening half-angle $\Delta\theta$ and a viewing angle θ_v the axis of the emission cone makes with $\theta = 0$ axis. The emitting shock front moves radially from $t = t_0$ and $r = r_0$ with the Lorentz factor $\gamma = 1/\sqrt{1 - \beta^2}$. Then the observed flux per unit frequency of a single pulse at the observed time T is given by

$$F_\nu(T) = \frac{2r_0^2\gamma^2}{\beta D^2(r_0/c\beta)} \times \int dt A(t) \frac{1 - \beta \cos\theta(T)}{1 - \beta \cos\theta(t)} \frac{\Delta\phi(t) f[\nu\gamma(1 - \beta \cos\theta(t))]}{[\gamma^2(1 - \beta \cos\theta(t))]^2}, \quad (1)$$

where $f(\nu')$ represents the spectral shape, and $1 - \beta \cos\theta(T) = (c\beta/r_0)(T - T_0)$, $1 - \beta \cos\theta(t) = [1 - \beta \cos\theta(T)]/[(c\beta/r_0)(t - T_0)]$ and $T_0 = t_0 - r_0/c\beta$. The value of $\Delta\phi(t)$ is π in the case of $\theta_v < \Delta\theta$ and $0 < \theta(t) \leq \Delta\theta - \theta_v$, while for the other case, it is given by

$$\Delta\phi(t) = \cos^{-1} \left[\frac{\cos\Delta\theta - \cos\theta(t)\cos\theta_v}{\sin\theta_v \sin\theta(t)} \right]. \quad (2)$$

The normalization of emissivity $A(t)$ is determined by the hydrodynamics. Here for simplicity we adopt the following functional form,

$$A(t) = A_0 \left(\frac{t - T_0}{r_0/c\beta} \right)^{-2} H(t - t_0) H(t_e - t), \quad (3)$$

where the emission ends at $t = t_e$ and the released energy at each distance r is constant. Shell emits at radius from r_0 to $r_e = \kappa r_0$, where $\kappa = t_e/t_0 > 1$. The quantity A_0 is a normalization constant. A pulse-starting time and ending time are given as

$$T_{start} = T_0 + (r_0/c\beta)(1 - \beta \cos(\max[0, \theta_v - \Delta\theta])) \quad , \quad (4)$$

$$T_{end} = T_0 + [(r_0/c\beta) + t_e - t_0](1 - \beta \cos(\theta_v + \Delta\theta)) \quad , \quad (5)$$

respectively. We adopt the following form of the comoving-frame energy spectrum,

$$f(\nu') = (\nu'/\nu'_0)^{1+\alpha} \exp[-(\nu'/\nu'_0)] \quad , \quad (6)$$

where α is a power law index. Mazets et al. (2005) derived a nonthermal spectrum with $\alpha = -0.7$ and an exponential cut-off at 800 keV, while Palmer et al. (2005) gave a nonthermal fit with $\alpha = -0.2$ and a cut-off at 480 keV. Although Hurley et al. (2005) reported a black-body spectrum ($\alpha = 1$) with a temperature higher than ~ 240 keV, at least a portion of the giant flare may be nonthermal because the spectrum was determined with low time resolution. A previous giant flare in SGR 0526-66 may also have had a nonthermal spectrum (Fenimore, Klebesadel & Laros 1996). In addition, some giant flares from SGRs in nearby galaxies (within 40 Mpc) may have been detected by BATSE as short GRBs whose spectra are likely nonthermal (Palmer et al. 2005). In this Letter, we assume a nonthermal spectrum, which is naturally produced by shocks in a relativistic outflow.

Equations (1), (3) and (6) are the basic equations to calculate the flux of a single pulse, which depends on following parameters: $\gamma\theta_v$, $\gamma\Delta\theta$, $\gamma\nu'_0$, $r_0/c\beta\gamma^2$, α , t_0 , t_e , and $r_0^2\gamma^2 A_0/D^2\beta$. We fix $\gamma\theta_v = 0$, $\gamma h\nu'_0 = 800$ keV, and $\alpha = -0.6$ in the following. Then we find out best fit values for other parameters: $\gamma\Delta\theta$, $r_0/c\beta\gamma^2$, and κ ($= t_e/t_0 = r_e/r_0$). We find that these parameters do not depend on α and $\gamma\nu'_0$ so much, even if we assume a black-body spectrum.

Figure 1 shows the result. The fit is surprisingly good considering the very simple model. The second pulse,

which has a duration of $T_{AB} \sim 50$ msec, and the associated power-law like decay lasting $T_{BC} \sim 500$ msec, are well fitted by our model with $\gamma\Delta\theta = 3.0$, $r_0/\gamma^2 = 2.6 \times 10^8$ cm, and $\kappa = 12.5$. We have checked that the uncertainty coming from the spectral shape is at most a factor of 2. We also show an example of the theoretical modeling for the first pulse ($t < 80$ msec) by black dotted line in the same figure. In this case the opening half-angle is not well constrained because the power-law like decay is masked by that of the second pulse. We can make a similar modeling for a bump at $t \sim 430$ msec, though it is not shown in the figure.

The opening angle of the jet is constrained by the light curve in a kinematical fashion (see Figures 1, 2). The duration of the brightest epoch ($80 \lesssim t \lesssim 130$ msec) is determined by the crossing time of the shell through the emitting region ($r_0 < r < r_e$) as

$$T_{AB} = \frac{(r_e - r_0)(1 - \beta)}{c\beta} \sim (\kappa - 1) \frac{r_0}{2c\gamma^2} \sim 50 \text{ msec.} \quad (7)$$

On the other hand, the following power-law like decay lasts for ~ 500 msec, which is approximately given by the angular spreading time

$$T_{BC} = \frac{r_e(1 - \cos\Delta\theta)}{c} \sim (\gamma\Delta\theta)^2 \kappa \frac{r_0}{2c\gamma^2} \sim 500 \text{ msec.} \quad (8)$$

In other words the wider the jet, the later the onset of the steep decay. Eliminating $r_0/2c\gamma^2$ from these equations, we derive $(\gamma\Delta\theta)^2 \sim 10(1 - \kappa^{-1}) \lesssim 10$ and hence $\gamma\Delta\theta \lesssim 3$. The uncertainty is at most a factor of 2. Furthermore, combining with $\gamma \gtrsim 25$ required to avoid pair formation (Nakar, Piran & Sari 2005), we obtain a firm upper limit, $\Delta\theta \lesssim 0.2$ radian, which is very similar to those of GRB jets inferred from the observed break in afterglow light curves (Harrison et al. 1999). In particular, we disfavor models with isotropic emission for the beginning epoch of the giant flare.

3. Discussions

We have shown that the initial spike of the giant flare SGR 1806-20 is well explained by emission from a relativistic jet directed toward us, and that the opening half-angle of the jet is less than 0.2 rad. Since the isotropic equivalent energy of the giant flare is 5×10^{46} ergs with assumed distance of 15 kpc (Terasawa et al. 2005), the collimation-corrected energy is less than 5×10^{44} ergs for $\Delta\theta < 0.2$ and the flare is rather economical than previously thought. This may alleviate an extreme situation that an isotropic flare demands almost all energy of dipole magnetic fields of SGR 1806-20. The size and the light curve of the radio afterglow from SGR 1806-20 also favor smaller energy $\sim 10^{44}$ - 10^{45} ergs (Cameron et al. 2005; Gaensler et al. 2005) than the isotropic equivalent energy of the flare, which also suggests a jet opening half-angle $\Delta\theta \sim 0.2$.

External shock scenario is unlikely because it is difficult to keep high Lorentz factor and have a steep decay at 500 msec. The third bump at $t \sim 430$ msec may be caused by an additional internal shock, while other reasons such

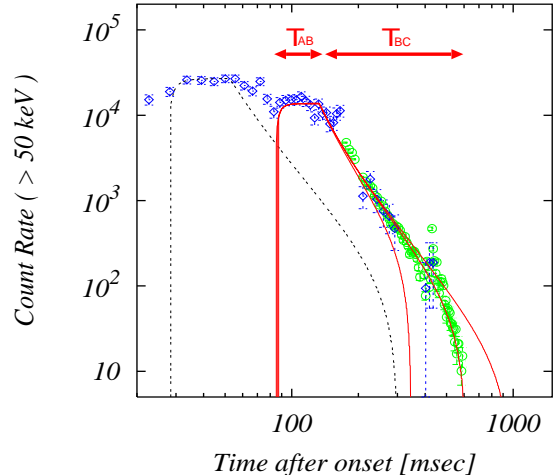


Fig. 1. Comparison of theoretically predicted light curves with the observed data. Green and blue points are background-subtracted MCP and CEM data, respectively (Terasawa et al. 2005). The second pulse and the following power-law like decay are modeled by red lines, which have $\Delta\theta = 2\gamma^{-1}$, $3\gamma^{-1}$, and $4\gamma^{-1}$ from left to right with $r_0 = 2.6 \times 10^8 \gamma^2$ cm and $r_e = 12.5r_0$. The rapid fading at $t \sim 600$ msec is most consistent with an opening half-angle of $\Delta\theta = 3\gamma^{-1}$. The black dotted line shows an example of the theoretical modeling for the first pulse ($t < 80$ msec).

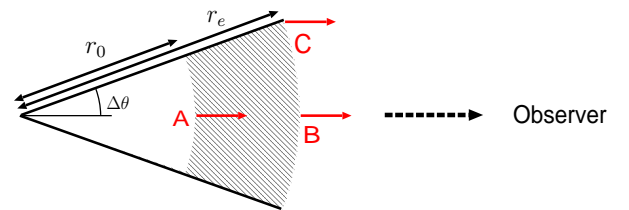


Fig. 2. A schematic picture of the jet emission. An observer resides far on the right side. A thin shell emits gamma-rays while it crosses the hatched region ($r_0 < r < r_e$). Each red arrow represents the emitted photon at each place. The observed duration ~ 50 msec of the second pulse ($80 < t < 130$ msec) in Figure 1 is determined by the shell crossing time, T_{AB} , i.e., the difference of the arrival time of two photons A and B that are emitted when the shell crosses radii r_0 and r_e , respectively. The observed duration of the power-law like decay after the second pulse ($130 < t < 600$ msec) in Figure 1 is determined by the angular spreading time, T_{BC} , i.e., the difference of the arrival time of two photons B and C emitted simultaneously. The wider the jet is, the later the rapid fading begins.

as inhomogeneities on the jet are possible since its peak flux is much smaller than the others.

A relativistic jet begins sideways expansion when the jet Lorentz factor becomes $\gamma \sim (\Delta\theta)^{-1}$. This epoch is observed at $T_{jet} \sim 9 \text{ min} (E_{45}/n_0)^{1/3} (\Delta\theta/0.1 \text{ rad})^2$, where E_{45} and n_0 is the total energy confined in the jet and the number density of the ambient matter. After that time, the jet decelerates abruptly. Hence in the epoch of radio observations (6–20 days after the flare), the outflow became Newtonian or sub-relativistic and nearly

isotropic, which is consistent with the radio observation. Nevertheless some degree of anisotropy may remain and produce the observed elliptical image and polarization of the radio afterglow (Gaensler et al. 2005).

It has been discussed that giant flares from other SGRs resemble classical GRBs in spectroscopic characters (Fenimore, Klebesadel & Laros 1996). This possibility is strengthened by our present result that the recent giant flare of SGR 1806-20 is a jetted emission like GRBs. However, in our scenario, there should be many more misaligned SGRs, which will show up only in isotropic emission. If the pulsating tails are isotropic emission, there should be many events consisting of only pulsating tails, though such events that are bright enough to trigger e.g. BATSE have not yet been reported. One possibility to resolve this “statistical” problem is that the pulsating tail is also collimated. According to the magnetar model, pulsating tail emission arises from an evaporating trapped fireball (Thompson & Duncan 1995; Thompson & Duncan 2001). Its size can be comparable to the radius of the magnetar. However, as discussed in Thompson & Duncan (2001), due to the QED effect, the radiative transport across the magnetic field lines is concentrated to the foot-point at the magnetar surface, which may be a reason for the collimation of the pulsating tail. The collimation angle would largely depend on the magnetic field configuration. However, the broad pulse profile (larger than 1 sec) of the tail disfavors the narrowly collimated pulsating tail emission. Another way to resolve the problem is to introduce some envelope around the main jet. In the GRB case, it is now widely argued whether the angular structure of the jet is uniform, Gaussian, power-law, or two-component (Zhang & Mészáros 2004). Similar to the GRB, it may be possible that the SGR jet also has a central core with $\Delta\theta \sim 0.1$ and an envelope with wider solid angle that can produce less energetic flares. Indeed, the past two giant flares show much smaller isotropic equivalent energies, $\sim 10^{44}$ ergs, while all three flares had pulsating tails with a similar energy $\sim 10^{44}$ ergs. If the central core is seen off-axis and the observer points to the envelope, such less energetic giant flares can be observed. At that time, the intense emission from the central core may be negligible because of the relativistic beaming effect. If such an envelope has a wide solid angle, the statistical problem can be resolved. Indeed, exponentially decaying tail after $t \sim 600$ msec recorded by BAT/*Swift* (Palmer et al. 2005) may be such an envelope emission.

The relativistic jet may not be generally launched along the rotation axis because the magnetic energy dominates over the rotational energy. The duration for the magnetar to eject a jet is less than the duration of a pulse, $t_{dur} < T_{AB} \sim 50$ msec. Thus the rotation angle during the jet ejection is at most $\vartheta_{rot} \sim 2\pi(t_{dur}/T_p) \lesssim 0.04(t_{dur}/50 \text{ msec})$ rad, where $T_p = 7.56$ sec is the rotational period of SGR 1806-20 (Hurley et al. 2005). Therefore, the overall opening half-angle is at most $\Delta\theta + \vartheta_{rot}/2$. Since this is comparable to $\Delta\theta$, the effect of the rotation of the magnetar may not be so large but may still affect the jet structure and generate the envelope as

discussed in the previous paragraph.

If the energy source of the flare was a dipole outer magnetic field and $\sim 10\%$ of its energy was converted to γ -rays as in the case of the isotropic flare, the spin down rate, $\dot{P} \propto B^2/P$, where P is the rotational period of the magnetar, would change by $\sim 10\%$ after the flare. Thus the isotropic flare might be tested by the observations of the spin down history.

It is widely believed that anomalous X-ray pulsars (AXPs) are the same kinds of objects as SGRs (e.g., Gavriil et al. 2004). Kulkarni et al. (2003) proposed the main difference between AXPs and SGRs is the time-dependent geometry of the magnetic fields, i.e., AXPs are older and less active than SGRs. Here we suggest that the viewing angle may also contribute to the different appearances of AXPs and SGRs. If we see the passive (active) part of the magnetar surface, the magnetar would show soft (hard) persistent X-ray emissions and look like AXP (SGR). This might be consistent with no giant flares from AXPs because the energetic jet core responsible for the giant flare is always misaligned.

We thank T. Terasawa for useful comments and providing GEOTAIL data. This work was supported in part by JSPS Research Fellowship for Young Scientists (RY), the Eberly Research Funds of Penn State and the Center for Gravitational Wave Physics under grants PHY-01-14375 (KI).

References

- Boggs, S. et al. 2005, GRB Coordinates Network, 2936
- Cameron, P. B. et al. 2005, astro-ph/0502428
- Cline, T. et al. 1980, ApJ, 237, L1
- Fenimore, E. E., Klebesadel, R. W., & Laros, J. G. 1996, ApJ 460, 964
- Frail, D., Kulkarni, S. R. & Bloom, J. 1999, Nature, 398, 127
- Gaensler, B. M. et al. 2005, astro-ph/0502393
- Gavriil, F. P., Kaspi, V. M., & Woods, P. M. 2004, Adv. Sp. Res. 33, 654
- Harrison, F. A. et al. 1999, ApJ, 523, L121
- Hjorth, J. et al. 2003, Nature, 423, 847
- Huang, Y. F., Dai, Z. G. & Lu, T. 1998, Chinese Physics Letters 15, 775
- Hurley, K. et al. 1999, Nature, 397, 41
- Hurley, K. et al. 2005, astro-ph/0502329
- Kulkarni, S. R. et al. 2003, ApJ, 585, 948
- Mazets, E. P. et al. 2005, astro-ph/0502541
- Nakar, E., Piran, T. & Sari, R. 2005, astro-ph/0502052
- Palmer, D. M. et al. 2005, astro-ph/0503030
- Piran, T. 1999, Phys. Rep., 314, 575
- Piran, T. 2004, Rev. Mod. Phys., 76, 1143
- Stanek, K. Z. et al. 2003, ApJ, 591, L17
- Terasawa, T. et al. 2005, astro-ph/0502315
- Thompson, C. & Duncan, R. C. 1995, MNRAS, 275, 255
- Thompson, C. & Duncan, R. C. 2001, ApJ, 561, 980
- Wang, X. Y. et al. 2005, ApJL in press (astro-ph/0502085)
- Woods, P. M. 2004, Adv. Sp. Res. 33, 630
- Yamazaki, R., Ioka, K. & Nakamura, T. 2003, ApJ, 591, 283
- Zhang, B. & Mészáros, P. 2004, Int. J. Mod. Phys. A19, 2385