Giant Flare of SGR 1806–20 from a Relativistic Jet

Ryo Yamazaki\textsuperscript{1,2}, Kunihito Ioka\textsuperscript{3}, Fumio Takahara\textsuperscript{2}, Noriaki Shibazaki\textsuperscript{4}

\textsuperscript{1}Department of Physics, Hiroshima University, Higashi-Hiroshima, 739-8526, Japan
\textsuperscript{2}Department of Earth and Space Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
\textsuperscript{3}Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\textsuperscript{4}Department of Physics, Rikkyo University, Nishi-Ikebukuro, Tokyo 171-8501, Japan

E-mail: ryo@theo.phys.sci.hiroshima-u.ac.jp

Abstract. The Japanese magnetospheric explorer, GEOTAIL, recorded a detailed light curve of the initial spike of a giant flare from SGR 1806–20 on 27 December 2004. We show that the observed light curve is well explained by emission from relativistically expanding fireballs, like those of gamma-ray bursts (GRBs). Especially, the observed rapid fading after 500 msec suggests that ejecta was collimated in a jet. We derived an upper limit on the jet opening half-angle of 0.2 rad, which is as narrow as those of GRBs. Observed proper motion of a centroid of a radio image also suggests the collimated outflow. Possible way to avoid the “statistical” problem is also discussed.

1. Introduction

Soft gamma repeaters (SGRs) are most likely highly magnetized neutron stars, so-called “magnetars” \cite{1, 2}. On 27 December 2004, a giant flare from SGR 1806–20 illuminated the Earth \cite{3, 4} with a gamma-ray flux of more than ~10\textsuperscript{6} times that of the typical cosmological gamma-ray bursts (GRBs), which are the most violent explosions in the universe. A giant flare has an initial spike lasting for about 600 msec with an isotropic equivalent energy of ~10\textsuperscript{46}−47 ergs, which is followed by a pulsating tail lasting 400 sec with energy of ~10\textsuperscript{44} ergs. The initial spike of the most recent flare was ~10\textsuperscript{2} times more energetic than the previous two events, while pulsating tails of the three events had comparable energies.

Because of the observed high flux density, most \(\gamma\)-ray detectors were saturated, except for particle detectors, such as GEOTAIL, which successfully recorded a burst light curve in the brightest initial spike \cite{5}. 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 was variable, and mainly consisted of two pulses. A gradual decay began after the second peak (\(t > 160\) msec) with a bump at \(t \sim 430\) msec. This was followed by a rapid fading after \(t \sim 500\) msec. Such a detailed light curve of the initial spike was measured for the first time. It brings us a new key to an understanding the mysterious, poorly understood SGRs.

The detection of radio afterglows after giant flares suggests that SGRs eject relativistic outflows \cite{6, 7, 8}. A relativistic motion is also implied by the nonthermal flare spectrum \cite{4, 9}; otherwise, pair formation occurs in a compact emission region, which makes thermal spectrum \cite{2, 10, 11}. Even if the spectrum is thermal \cite{3}, its hyper-Eddington luminosity implies a relativistic motion \cite{12}. 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 relativistic outflow, and the pulsating tail may come
from evaporating trapped fireballs. The kinetic energy of the outflow inferred from the radio
afterglow is $\sim 10^{44} - 10^{45}$ ergs [6, 7], which is much smaller than the isotropic equivalent energy
of the initial $\gamma$-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
to $\sim 100$ times) during its active time ($\sim 10^4$ yrs) unless the emission is collimated, or there
is another 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 [13]. Energy is carried away from a compact source as the kinetic energy of jets.
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, the outflow interacts with ambient circumstellar matter, producing external shocks, which
are responsible for afterglows on much longer time scales at various wavelengths, such as radio,
optical, and X-ray bands.

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. Because the shell at higher latitude from the LOS has a lower
velocity toward the observer, the emission becomes dimmer and softer as time passes because of
the relativistic Doppler effect, which very well explains the observed decay during between 200
and 400 msec. If the emission is spherical (isotropic), however, such a decay should continue
beyond $t > 600$ 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 a 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 that radiates photons when the shell is located at radii from $r_0$
to $r_e$ [14, 15]. 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 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 $\kappa = r_e/r_0 = 12.5$. The uncertainty coming from the spectral shape is at most a factor of 2.

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 ($80 < t < 130$ msec) is determined by the
crossing time of the shell through the emitting region ($r_0 < r < r_e$) as

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

On the other hand, the following decay lasts for $\sim 500$ msec, which is approximately given by
the angular spreading time,

$$ T_{BC} = \frac{r_e(1 - \cos \Delta \theta)}{c} \sim (\gamma \Delta \theta)^2 \kappa \frac{r_0}{2c\gamma^2} \sim 500 \text{ msec.} \quad (2) $$
Figure 1. Comparison of theoretically predicted light curves with the observed data [15]. The circles and triangles are background-subtracted MCP and CEM data, respectively [5]. The second pulse and the following decay are modeled by thick-solid 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 dashed line shows an example of the theoretical modeling for the first pulse ($t < 80$ msec).

Figure 2. Schematic picture of the jet emission [15]. 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 arrow represents the emitted photon at each place. The observed duration, $\sim 50$ 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 is the jet, the later does the rapid fading begin.

In other words, the wider is the jet, the later is the onset of the steep decay. By eliminating $r_0/2c\gamma^2$ from these equations, we derive $(\gamma \Delta\theta)^2 \sim 10(1 - \kappa^{-1}) < 10$, and hence $\gamma \Delta\theta < 3$. The uncertainty is at most a factor of 2. Furthermore, by combining with $\gamma > 25$ required to avoid pair formation [11], we obtain a firm upper limit, $\Delta\theta < 0.2$ rad, which is very similar to those of GRB jets inferred from the observed break in afterglow light curves [13].

3. Discussions
Since the isotropic equivalent energy of the giant flare is $5 \times 10^{46}$ ergs with an assumed distance of 15 kpc [5], the collimation-corrected energy is less than $5 \times 10^{44}$ ergs for $\Delta\theta < 0.2$ and the flare is rather more 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 a smaller energy of $\sim 10^{44-45}$ ergs [6, 7] than the isotropic equivalent energy of the flare, which also suggests a jet opening half-angle of $\Delta\theta \sim 0.2$.

Observed proper motion of a centroid of a radio image [8] may support the collimated outflow. The relativistic jet is significantly decelerated due to the sideways expansion within ten minutes after the giant flare [15], so that the radio image expands non-relativistically [8]. Introducing a non-relativistic component besides the relativistic jet, observed expansion law of the radio image may also be explained [16].
It has been discussed that giant flares from other SGRs resemble classical GRBs in spectroscopic characters [17]. 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 to introduce some envelope around the main jet [15]. In the GRB case, it is now widely argued whether the angular structure of the jet is uniform, Gaussian, power-law, or two-component [13]. 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 a wider solid angle that can produce less energetic flares. Indeed, the past two giant flares showed much smaller isotropic equivalent energies, $\sim 10^{44}$ ergs, while all three flares had pulsating tails with a similar energy of $\sim 10^{44}$ 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, an exponentially decaying tail after $t \sim 600$ msec recorded by BAT on Swift [4] may be such an envelope emission.

Acknowledgments
We thank T. Terasawa for useful comments and providing GEOTAIL data. This work was supported in part by JSPS Research Fellowship for Young Scientists (R.Y.).

References
[1] Thompson C & Duncan R C 1995 Mon. Not. Roy. Astron. Soc. 275 255
[2] Thompson C & Duncan R C 2001 Astrophys. J. 561 980
[3] Hurley K et al. 2005 Nature 434 1098
[4] Palmer D M et al. 2005 Nature 434 1107
[5] Terasawa T et al. 2005 Nature 434 1110
[6] Cameron P B et al. 2005 Nature 434 1112
[7] Gaensler B M et al. 2005 Nature 434 1104
[8] Taylor G B et al. 2005 Astrophys. J. 634 L93
[9] Mazets E P et al. 2005 Preprint astro-ph/0502541
[10] Huang Y F, Dai Z G and Lu T 1998 Chin. Phys. Lett. 15 775
[11] Nakar E, Piran T and Sari R 2005 Preprint astro-ph/0502052
[12] Wang X Y, Wu X F, Fan Y Z, Dai, Z G and Zhang B 2005 Astrophys. J. 623 L29
[13] Zhang B and Mészáros P 2004 Int. J. Mod. Phys. A 19 2385
[14] Yamazaki R, Ioka K and Nakamura T 2003 Astrophys. J. 591 283
[15] Yamazaki R, Ioka K, Takahara F and Shibazaki N 2005 Publ. Astron. Soc. Japan 57 L11
[16] Dai Z G, Wu X F, Wang X Y, Huang Y F and Zhang B 2005 Astrophys. J. 629 L81
[17] Fenimore E E, Klebesadel R W and Laros J G 1996 Astrophys. J. 460 964