COMPARATIVE STUDY OF THE INITIAL SPIKES OF SOFT GAMMA-RAY REPEATER GIANT FLARES IN 1998 AND 2004 OBSERVED WITH GEOTAIL: DO MAGNETOSPHERIC INSTABILITIES TRIGGER LARGE-SCALE FRACTURING OF A MAGNETAR’S CRUST?

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ABSTRACT

We present the unsaturated peak profile of the giant flare from SGR 1900+14 on 1998 August 27. This was obtained by the particle counters of the Low Energy Particles instrument on board the Geotail spacecraft. The observed peak profile revealed four characteristic features: an initial steep rise, an intermediate rise to the peak, an exponential decay, and a small hump in the decay phase. From this light curve, we found that the isotropic peak luminosity was $3.3 \times 10^{46}$ erg s$^{-1}$ and that the total energy was $4.3 \times 10^{44}$ ergs s$^{-1}$ ($E \approx 50$ keV), assuming that the distance to SGR 1900+14 is 15 kpc and that the spectrum is optically thin thermal bremsstrahlung with $kT = 240$ keV. These values are consistent with the previously reported lower limits derived from Ulysses and Konus-Wind observations. A comparative study of the initial spikes of the SGR 1900+14 giant flare in 1998 and of the SGR 1806−20 giant flare in 2004 is also presented. The timescale of the initial steep rise shows a magnetospheric origin, while the timescale of the intermediate rise to the peak indicates that it originates from crustal fracturing. Finally, we argue that the four features and their corresponding timescales provide us with a clue to identify extragalactic soft gamma-ray repeater giant flares among short gamma-ray bursts.

Subject headings: gamma rays: bursts — gamma rays: observations — stars: individual (SGR 1806−20, SGR 1900+14) — stars: magnetic fields — stars: neutron

Online material: color figures

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) were first discovered as high-energy burst sources in the late 1970s (Mazets & Golenetskii 1981). Once SGRs enter burst-active phases, they produce a lot of short-duration ($\sim0.1$ s) energetic ($\sim10^{46}$ ergs) soft gamma-ray bursts. These bursts were distinguished from cosmological gamma-ray bursts (GRBs) by their soft spectra and their repeated activities. Furthermore, as rare events, SGRs emit extremely bright giant flares (GFs). A GF lasts for several hundred seconds, and its isotropic total energy amounts to $10^{41}$–$10^{46}$ ergs. So far, only three have been recorded. On 1979 March 5, the first GF was detected from SGR 0526−66 by the Venera spacecraft (Mazets et al. 1979). The second GF was observed from SGR 1900+14 on 1998 August 27 (Hurley et al. 1999; Mazets et al. 1999; Feroci et al. 2001). Recently, SGR 1806−20 emitted a third GF on 2004 December 27 (Terasawa et al. 2005; Hurley et al. 2005; Palmer et al. 2005; Mereghetti et al. 2005; Schwartz et al. 2005). The overall time profile of each GF is characterized by a very intense, spectrally hard initial spike, whose duration is $\leq 0.5$ s, and a subsequent pulsating tail, which has a softer spectrum and lasts for some hundreds of seconds. After the GFs, radio afterglows were observed from SGR 1900+14 (Frail et al. 1999) and from SGR 1806−20 (Gaensler et al. 2005; Cameron et al. 2005).

SGRs have slow spin periods (5–8 s) and rapid spin-down rates ($10^{-11}$ to $10^{-10}$ s s$^{-1}$; Kouveliotou et al. 1998; Kouveliotou et al. 1999). Assuming magnetic dipole radiation, we can estimate the magnetic fields of SGRs to be $10^{14}$–$10^{15}$ G, and SGRs are recognized as magnetars (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). According to the magnetar model, the energy source of both recurrent bursts and GFs is the ultrastrong magnetic field: stored magnetic energy inside a magnetar is suddenly released via the cracking of a magnetar’s crust, and the large-scale crustal fracturing produces GFs. Similar to earthquakes, the power-law distribution of the radiated energy of the repeated burst and the lognormal distribution of waiting times between successive bursts are reported (Cheng et al. 1996; Gögüş et al. 2000). These observations also support the idea that SGR bursts originate from starquakes.

In this Letter, we first focus on the SGR 1900+14 GF on 1998 August 27. This flare was detected by gamma-ray instruments on the Ulysses, Konus-Wind, and BeppoSAX satellites (Hurley et al. 1999; Mazets et al. 1999; Feroci et al. 2001). However, the flare was so intense that these instruments underwent severe dead time or had pulse pileup problems. Consequently, the time profile during the most intense period was not obtained, and only the lower limits of the peak flux intensity and fluence were reported (Hurley et al. 1999; Mazets et al. 1999). Here we present the clear peak profile of the SGR 1900+14 GF on 1998 August 27. The profile was recorded by the Low Energy Particles instrument (hereafter LEP; Mukai et al. 1994) on board the Geotail spacecraft, whose principal objective is to study the Earth’s magnetosphere. The light curve for the first 350 ms of the GF is unsaturated and has a high time resolution of 5.58 ms. We also show the energetics of the flare.

Second, we present a comparative study of the initial spikes of SGR GFs in 1998 and 2004, the latter of which was also detected by the same instrument (Terasawa et al. 2005). From both of the light curves, we extract the characteristics of the initial spikes of SGR GFs, focusing on the timescales discovered during the initial spikes. Finally, we argue that the observed timescales may provide us with a clue to identify extragalactic SGR giant flares among short GRBs.
2. INSTRUMENTATION AND OBSERVATION

The LEP is designed to measure three-dimensional velocity distributions of the Earth's magnetospheric ions and electrons. It consists of two nested sets of quadspherical electrostatic analyzers, one analyzer to select ions and the other to select electrons. At the receiving end of the ion and electron optics, seven microchannel plate detectors (MCPs) and seven channel electron multipliers (CEMs) are used, respectively. During the SGR 1806–20 GF in 2004, the peak flux was so intense that the MCPs were saturated during the first 150 ms. Alternatively, the peak profile was derived from the CEMs, because the CEMs are much less sensitive to gamma rays than the MCPs are. After the most intense period, the MCPs recovered from the saturation and observed the decay profile clearly. On the other hand, during the SGR 1900+14 GF in 1998, we obtained the peak profile from the MCPs. The peak flux of the 1998 GF was about one-tenth of that of the 2004 GF (see below), and hence the MCPs did not suffer severe saturation. The CEMs showed count increases (≤20) corresponding to those of the MCPs. However, since the background electron counts for CEMs were high (~50–80), we did not use the CEM data for the analysis of the SGR 1900+14 GF.

The LEP records the data every 15/8192 of the spacecraft spin period over 32 sequences, followed by a gap of 1/256 of the spin period. The spacecraft spin period was 3.046 s on 1998 August 27, leading to a 3.046 × (15/8192) = 5.58 × 10⁻³ s = 5.58 ms time resolution. This is slightly different form the 5.48 ms time resolution of the SGR 1806–20 GF observation in 2004, during which the spin period was 2.993 s.

In this report, we use the LEP calibration, in which the effective energy range and the detection efficiency are >50 keV and ~1% against incident photons, respectively. Since the LEP was not designed to measure gamma rays, this calibration was made after the launch of the Geotail spacecraft through the analyses of solar flare photons for which the Hard X-ray Telescope on board the Yohkoh satellite (Kosugi et al. 1991) provided photon energy spectra and intensities. Recently, we have made (1) GEANT4 simulations based on the detailed mass model of the LEP, satellite structure, and other instruments and (2) the laboratory measurements of the detection efficiency of the MCP (Tanaka et al. 2007), both of which have successfully reproduced what were obtained from the solar flare photon analyses. In addition, we found from the GEANT4 simulations that the effect of the rotation of the spacecraft was negligibly small around the spin-phase angles corresponding to the two GFs.

Figure 1 shows the first 350 ms unsaturated peak profile of the GF from SGR 1900+14 on 1998 August 27. Dead-time and saturation effects are negligible for the count rates smaller than ~1000 counts per 5.58 ms; only the peak count at  5.58 ms was dead-time–corrected. The shaded bars in Figure 1 indicate the instrumental data gaps of 12 ms. The onset time was dead-time–corrected. The shaded bars in Figure 1 indicate what were obtained from the solar flare photon analyses. In Tanaka et al. (2007), both of which have successfully reproduced what were obtained from the solar flare photon analyses. In addition, we found from the GEANT4 simulations that the effect of the rotation of the spacecraft was negligibly small around the spin-phase angles corresponding to the two GFs.

To convert physical quantities such as an energy flux from the observed count rates, we need an assumption on the photon energy spectrum, because the LEP detected integrated photon numbers above 50 keV. We assume the $kT = 240$ keV optically thin thermal bremsstrahlung spectrum that was obtained from the Konus-Wind instrument (see Fig. 6 of Mazets et al. 1999). After that, it increased again with an $e$-folding time of 16 ± 2.5 ms for $t = 22–50$ ms and reached a flat-top second peak in 60–120 ms. Finally, the exponential decay was clearly observed, and a decay time of 23 ± 1.6 ms was obtained during $t = 120–160$ ms. Note that a small hump was seen around 310 ms, which was also observed with the Konus-Wind instrument (Fig. 6 of Mazets et al. 1999).

To convert physical quantities such as an energy flux from the observed count rates, we need an assumption on the photon energy spectrum, because the LEP detected integrated photon numbers above 50 keV. We assume the $kT = 240$ keV optically thin thermal bremsstrahlung spectrum that was obtained from Ulysses observation (Hurley et al. 1999). Resultant physical quantities are tabulated in Table 1, combined with the Venera observation of the SGR 0526–66 GF in 1979 (Mazets et al. 1999) and the Geotail observation of the SGR 1806–20 GF in 2004 (Terasawa et al. 2005). We found that the peak luminosity and the total emitted energy are $2.3 × 10^{44} d_{15}^2$ erg s⁻¹ and $4.3 × 10^{44} d_{15}^3$ ergs ($E \approx 50$ keV), respectively. Here we assume that the distance to SGR 1900+14 is 15 kpc (Vrba et al. 2000) and that $d_{15} = (d/15$ kpc). We also found that the total energy of this GF is about 130 times smaller than that of the 2004 December 27 GF from SGR 1806–20, although it is reported that the energy emitted during the pulsating tail in each GF is comparable ($E_{tail} \sim 10^{44}$ ergs; see Table 1) (Hurley et al. 2005; Palmer et al. 2005; Mazets et al. 1999). Note that this difference by a factor of 130 is the same order of the radio observations: the radio afterglow of the SGR 1900+14 GF is approximately...
500 times fainter than that of the SGR 1806–20 GF (Frail et al. 1999; Gaensler et al. 2005; Cameron et al. 2005).

3. DISCUSSION

We observed two SGR GFs out of every three recorded, from SGR 1900+14 in 1998 and SGR 1806–20 in 2004. Here we present a comparative study and extract the characteristics of the initial spikes of the SGR GFs. Figures 1 and 2 show the light curves of the initial spikes of the SGR 1900+14 GF and the SGR 1806–20 GF, respectively. Figure 3 shows the detailed initial rise profiles of both GFs. From these light curves, we identify four common features: (1) an initial steep rise, (2) an intermediate rise to the peak, (3) an exponential decay, and (4) a small hump in the decay phase. The calculated e-folding times corresponding to the structures of features 1–3 and the timing when we observed the structure (feature 4) are tabulated in Table 1.

First, we focus on the initial steep rise (feature 1). The observed initial rise time of the SGR 1900+14 GF is ∼1.6 ms. This is comparable to the initial rise time of ∼1.3 ms observed in the SGR 1806–20 GF, which implies that the same physical mechanism is producing the initial rapid energy releases of these two GFs. Note that in the leading edge of the initial spike of the SGR 1806–20 GF, Swift and RHESSI observed similar timescales (Swift: ∼0.3 ms; RHESSI: 0.38 ± 0.04 ms; Palmer et al. 2005; Boggs et al. 2007). These correspond to our observation of a ∼1.3 ms initial rise time. According to the reconnection model of GFs (Thompson & Duncan 1995; Duncan 2004), reconnection typically occurs at a fraction of the Alfvén velocity (Thompson & Duncan 1995; Duncan 2004), and this interpretation leads to \( t_{\text{mag}} \sim L/0.1V_{A} \sim 0.3 \) (L/10 km) ms, where \( L \) is the scale of the reconnection-unstable zone and \( V_{A} \) is the Alfvén velocity in the magnetosphere. This theoretical timescale \( t_{\text{mag}} \) seems consistent with the observation of the initial rise time.

Second, we consider the intermediate rise to the peak (feature 2). The observed e-folding rise time of the SGR 1900+14 GF is 3.1 ms, which is shorter than the 9.4 ms rise time observed in the SGR 1806–20 GF by factor of about 3.0. If this timescale is limited by the propagation of a fracture, we can infer the fracture size in km as \( l \sim 4 \) km (\( t_{\text{mag}}/4 \) ms) (Thompson & Duncan...
Using this, the fracture size of SGR 1900+14 is estimated to be ~3.1 km, and that of SGR 1806–20 is estimated to be ~9.4 km. It should be noted that our 9.4 ms rise time observed in the SGR 1806–20 GF differs by factor of ~2 from 4.9 ms derived from the Cluster spacecraft observation of the same GF (Schwartz et al. 2005). The origin of the difference between these timescales is not understood, but it could possibly be attributed to the different energy coverages of the detectors. Unfortunately, since the energy response of the Cluster detectors against incoming X-ray and gamma-ray photons was not calibrated, a further quantitative comparison between Geotail and Cluster is not possible.

In the initial spike of the SGR 1900+14 GF in 1998, we found a deep dip and a rebrightening following a sharp peak (Fig. 1). We propose that this dip explains the temporal recovery of the counter on the Konus-Wind (Mazets et al. 1999), since the dip and the recovery occurred nearly simultaneously. Note that Swift and RHESSI also detected a dip and a rebrightening in the leading edge of the initial spike of the SGR 1806–20 GF (Palmer et al. 2005; Boggs et al. 2007) that could not be resolved by the Geotail observation. This association implies that the dip and rebrightening are common features of the initial spikes of the SGR GFs, although a theoretical interpretation is unclear.

Third, we concentrate on the exponential decay (feature 3). The decay time of the SGR 1900+14 GF is 23 ms. This is shorter than the 66 ms decay time of the SGR 1806–20 GF by factor of 2.9, which roughly coincides with the factor 3.0 found in the decay time of the SGR 1900+14 GF (Palmer et al. 2005). This timescale is also the same order of magnitude as the decay times presented above. These two similarities found in the light curves also support the SGR hypothesis. A hump in a decay phase was not seen in the light curve of GRB 051103. This is explicable in terms of the detector’s detection limit, because the flux of the hump, if it exists, is expected to be about one-hundredth of the peak flux.

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