Repeated injections of energy in the first 600 ms of the giant flare of SGR 1806-20

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\textbf{ABSTRACT}

The massive flare of 27 December 2004 from the soft $\gamma$-ray repeater SGR 1806-20, a possible magnetar\textsuperscript{1-3}, saturated almost all $\gamma$-ray detectors\textsuperscript{4-7}, meaning that the profile of the pulse was poorly characterized. An accurate profile is essential to determine physically what was happening at the source. Here we report the unsaturated $\gamma$-ray profile for the first 600 ms of the flare, with a time resolution of 5.48 ms. The peak of the profile (of the order of $10^7$ photons cm$^{-2}$ s$^{-1}$) was reached $\sim 50$ ms after the onset of the flare, and was then followed by a gradual decrease with superposed oscillatory modulations possibly representing repeated energy injections with $\sim 60$ ms intervals. The implied total energy is comparable to the stored magnetic energy in a magnetar ($\sim 10^{47}$ erg) based on the dipole magnetic field intensity ($\sim 10^{15}$ G), suggesting either that the energy release mechanism was extremely efficient or that the interior magnetic field is much stronger than the external dipole field\textsuperscript{2}. 
At the onset of the giant flare of SGR 1806-20, plasma particle detectors on the Geotail spacecraft detected an extremely strong signal of soft $\gamma$-ray photon fluxes (integrated above $\sim 50$ keV) during the initial intense phase of the giant flare ($t=0$-600 ms). Figure 1 shows the count profiles of two detectors, $N_{\text{MCP}}$ (red symbols) from the microchannel plates (MCPs), and $N_{\text{CEM}}$ (blue symbols) from channel electron multipliers (CEMs), where $N_{\text{CEM}}$ is scaled by a factor of 280 to account for the sensitivity difference. The onset time ($t=0$) corresponded to 21 h 30 min 26.35 s Universal Time (UT), which was consistent with the expected arrival time of the onset signal at the Geotail position. To understand how the flare energy release occurred, the detailed time profile of the flare is important. Before the onset $N_{\text{MCP}}$ was at the background level ($<\sim 11$ counts, shown by a black arrow), and then increased to 839 counts within 5.48 ms, so that the e-fold time of the initial rise was shorter than $\sim 1.3$ ms. After the intermediate level of 1,330 counts at $t=5.48$ ms, the MCPs were saturated and $N_{\text{MCP}}$ could not be determined until $\sim 176$ ms. Between $t=22.7$ and 170 ms, we could obtain $N_{\text{CEM}}$ values instead. The scaled $N_{\text{CEM}}$ increased to 25,900 at $t=33.6$ ms, thus giving an e-fold time of 9.5 ms. (A data gap between $t=11.0$ and 22.7 ms shown by the leftmost grey bar was due to the scheduled instrumental operation and not caused by the flare itself.) Between $t=33.6$ and 55.5 ms the scaled $N_{\text{CEM}}$ stayed at the peak level of $\sim 25,000$-27,000. After $t=61$ until 170 ms the scaled $N_{\text{CEM}}$ decreased gradually with oscillatory modulation, which suggests repeated energy injections at $\sim 60$ ms intervals. (Note that a similar injection profile was also seen during the impulsive phase of the giant flare of SGR0526-66 on 5 March 1979 (ref.8).) After 176 ms $N_{\text{MCP}}$ became available again and showed a continuing exponential decay with an e-fold time of $\sim 66$ ms until $t=380$ ms. The decay profile of scaled $N_{\text{CEM}}$ available for $t=210$-308 ms is consistent with that of $N_{\text{MCP}}$. Between $t=397$ and 500 ms several humps were seen on the profile of $N_{\text{MCP}}$. Although less significant, scaled $N_{\text{CEM}}$ showed a similar hump for $t=402$-451 ms. (Note that the same humps were also detected by the BAT detector on the Swift spacecraft.) The physical origin of these humps is not clear at the moment, but may represent some additional energy-releasing process. After $t=470$ ms, $N_{\text{MCP}}$ again decayed with an e-fold time of $\sim 57$ ms.

To convert the observed count rates to physical quantities such as energy flux, we need the energy spectrum information, which was not available from the Geotail observation alone. We have therefore taken three reported function forms at the peak of the giant flare$^{4,5,7}$ (Table 1) and integrated them above 50 keV. We then found that the resultant estimations of photon number flux, energy flux and fluence (for $t=0$-600 ms) are almost independent of the choice of the energy spectrum, and are $\sim 2.5 \times 10^7$ photons cm$^{-2}$ s$^{-1}$, $\sim 20$ erg s$^{-1}$ cm$^{-2}$ and $\sim 2$ erg cm$^{-2}$, respectively. The corresponding total energy radiated from SGR 1806-20 is estimated to be $\sim 5 \times 10^{46}$ $(\Omega/4\pi) \, d_{15}^2$ erg, where $d_{15}$ is the distance scaled by 15 kpc and $\Omega$ is the solid angle of the radiation. Here we note that the solid-angle factor $(\Omega/4\pi)$ is not likely to be
as small as $10^{-2}$, as is typically assumed for relativistic jets for GRBs. $(\Omega/4\pi) > 0.1$ is more likely for the intense initial spikes of SGRs because they have been seen in all the three giant flares of SGRs that could have been detected without them. Therefore the presence of a very efficient mechanism is implied, which promptly releases (on a timescale of $\sim 60$ ms) a major fraction of the stored magnetic energy in a magnetar, $E_{\text{mag}} \approx 1.7 \times 10^{47}B_{15}^2R_6^3$ erg (where $B_{15}$ and $R_6$ are the internal magnetic field scaled by $10^{15}$ G and the radius of the magnetar scaled by $10^6$ cm). Alternatively, as suggested by ref. 2, the internal magnetic field could be as strong as $(5-10) \times 10^{15}$ G so as to permit the emission of multiple giant flares over the lifetime of a magnetar.

As we noted above, there were humps in the light curve of the 2004 giant flare at $t=400-500$ ms. Similar humps were also observed at 200-600 ms after the onset of another giant flare of SGR 1900+14 on 27 August 1998, whose total energy is smaller by a factor of $\sim 100$ than the 2004 giant flare. From similarities in the timings of the humps despite the large difference in the total energies, we suggest that the humps more probably represented continuing energy injections, rather than the results of interactions of the flare ejecta with environmental matter.

Methods

The Low Energy Particle (LEP) experiment aboard Geotail consists of an ion detector with seven independent MCPs and electronics systems, and an electron detector with seven independent CEMs and electronics systems, both of which are designed to measure plasma particles in the solar wind and magnetospheric environment. When the giant flare occurred, Geotail was at $(-1.5997 \times 10^5,-97945,-19671)$ km using the Geocentric Solar Inertia (GCI) coordinates (J2000), which was in the solar wind about $\sim 10$ earth radii upstream from the bow shock. Although MCPs and CEMs kept measuring the solar wind ions and electrons throughout the giant flare interval, these particles were being selected electrostatically and came into the detectors mainly at some limited timings that fortunately did not overlap the giant flare interval: the contribution of solar wind ions to $N_{\text{MCP}}$, which is the sum of counts over seven MCPs, was at most 30, and thus was negligible for the study of intense $\gamma$-ray photons. On the other hand, during subintervals ($t < 10$ ms, 175 ms $< t < 200$ ms, 320 ms $< t < 400$ ms and 450 ms $< t < 600$ ms), $N_{\text{CEM}}$, which is the sum of counts over seven CEMs, was affected by solar wind electrons, and was not available for the $\gamma$-ray photon detection.

Another fortunate factor was that the angular distance between the Sun and SGR 1806-20 was $\sim 5$ degrees, so that previous knowledge of the ‘calibration’ of the LEP detector to
be used as a soft $\gamma$-ray photon counter on the basis of solar flare photon analysis was directly applicable to the interpretation of the observed characteristics of photons from SGR 1806-20. By comparing the count rates of MCP and CEM with the hard X-ray$^{11}$ and $\gamma$-ray$^{12}$ data from the Yohkoh space solar observatory during major solar flares in 1997-2001 (ref.13), we have seen that MCP and CEM are sensitive to soft $\gamma$-ray photons above $\sim$ 50 keV, where their sensitivities are evaluated as the product $[\epsilon S]$ of quantum efficiency $\epsilon$ and effective detection area $S$ summed over seven MCPs and seven CEMs against $\gamma$-ray photons. (Here $\epsilon$ is defined to include not only the detector response itself but also the attenuation factor inside the spacecraft.) From the spectral information provided by the Yohkoh observations, we have calculated photon fluxes in two energy ranges, L (50-500 keV) and H (above 500 keV), and then estimated $[\epsilon S]_{\text{MCP,L}}$ and $[\epsilon S]_{\text{MCP,H}}$ separately for these two energy ranges. (This separation is possible because the energy spectra of incident solar $\gamma$-ray photons differ from event to event.) Figure 2 shows the calibration result. Along the line of sight towards SGR 1806-20, we have found that $[\epsilon S]_{\text{MCP,L}}=(0.19\pm0.06)$ cm$^2$ and $[\epsilon S]_{\text{MCP,H}}=(0.22\pm0.16)$ cm$^2$ where systematic errors are included. The estimation of $[\epsilon S]_{\text{CEM}}$ has been also done with solar flare $\gamma$-ray photons, and the result is summarized as $[\epsilon S]_{\text{CEM}}\approx1/280$ of $[\epsilon S]_{\text{MCP}}$. The smallness of $[\epsilon S]_{\text{CEM}}$ as compared with $[\epsilon S]_{\text{MCP}}$ is consistent with the difference in physical sizes of CEMs (millimetres) and MCPs (several centimetres).

It is noted that $[\epsilon S]_{\text{MCP}}$ obtained above is by a factor $10^{-2}$-$10^{-3}$ smaller than those of conventional $\gamma$-ray detectors. Nonetheless MCPs were saturated during $\sim$ 150 ms of the onset of the giant flare of SGR 1806-20. We have made that the dead-time analysis for MCPs and found that the characteristic dead time is $\sim$ 4.3 $\mu$s, which is consistent with the pre-flight calibration of the LEP system as well as the calculated circuit time constant. $N_{\text{MCP}}$, shown in Fig. 1, is after the dead-time correction, which becomes significant above $\sim$ 1,000 counts. On the other hand, CEMs, which are two orders of magnitude less sensitive than MCPs, were found to be free from the saturation effect even at the peak of the giant flare.

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REFERENCES

1. Thompson, C. & Duncan, R. C. The soft gamma repeaters as very strongly magnetized neutron stars-I. Radiative mechanism for outbursts. *MNRAS* 275, 255-300 (1995).

2. Thompson, C. & Duncan, R. C. The soft gamma repeaters as very strongly magnetized neutron stars. II. Quiescent neutrino, X-ray, and Alfven wave emission. *Astrophys. J.* 473, 322-342 (1996).

3. Thompson, C. & Duncan, R. C. The giant flare of 1998 August 27 from SGR1900+14. II. Radiative mechanism and physical constraints on the source. *Astrophys. J.* 561, 980-1005 (2001).

4. Hurley, K. et al. A tremendous flare from SGR 1806-20 with implications for short-duration gamma-ray bursts. *Nature* (this issue), astro-ph/0502329 (2005).

5. Mazets, E. P. et al. The Konus-Wind and Helicon-Coronas-F detection of the giant $\gamma$-ray flare from the soft $\gamma$-ray repeater SGR 1806-20. astro-ph/0502541 (2005).

6. Mereghetti, S. et al. The first giant flare from SGR 1806-20: observations with the INTEGRAL SPI Anti-Coincidence Shield. *Astrophys. J. Letters* (in press), astro-ph/0502577 (2005).

7. Palmer, D. M. et al. Gamma ray observations of a giant flare from the magnetar SGR 1806-20. *Nature* (this issue), astro-ph/050303 (2005).

8. Barat, C. et al. Fine time structure in the 1979 March 5 gamma ray burst. *Aston. Astrophys.*, 126, 400-402 (1983).

9. Mazets, E. P. et al. Activity of the soft gamma repeater SGR 1900+14 in 1998 from Konus-Wind observations: 2. The giant August 27 outburst. *Astron. Letters* 25, 635-648 (1999).

10. Mukai, T. et al. The low energy particle (LEP) experiment onboard the Geotail satellite. *J. Geomag. Geoelectr.* 46, 669-692 (1994).

11. Kosugi, T. et al. The hard X-ray telescope (HXT) for the solar-A mission. *Solar Phys.* 136, 17-36 (1991).

12. Yoshimori, M. et al. The wide band spectrometer on the solar-A. *Solar Phys.* 136, 69-88 (1991).
13. Matsumoto, Y. et al. A statistical study of gamma-ray emitting solar flares observed with Yohkoh. *PASJ* 57, 211-220 (2005)

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| Model          | Photon flux (photons cm$^{-2}$ s$^{-1}$) | Energy flux$^1$ (erg cm$^{-2}$ s$^{-1}$) | Fluence$^2$ (erg cm$^{-2}$) | Isotropic luminosity (erg s$^{-1}$) | Isotropic total energy (erg) |
|----------------|----------------------------------------|----------------------------------------|----------------------------|-------------------------------------|----------------------------|
| Planck         | (2.5$^{+0.1}_{-0.1}$) x 107            | 19$^{+3}_{-2}$                         | 2.0$^{+0.2}_{-0.2}$        | (5.1$^{+1.3}_{-1.3}$) x 10$^{47}$ d$_{15}$ | (5.4$^{+2.3}_{-2.3}$) x 10$^{46}$ d$_{15}$ |
| $E^{-0.2}$ exp(-E/480) | (2.5$^{+0.1}_{-0.1}$) x 107            | 18$^{+2}_{-3}$                         | 1.9$^{+0.4}_{-0.4}$        | (4.9$^{+1.0}_{-1.0}$) x 10$^{47}$ d$_{15}$ | (5.2$^{+1.2}_{-1.2}$) x 10$^{46}$ d$_{15}$ |
| $E^{-0.7}$ exp(-E/800) | (2.5$^{+0.1}_{-0.1}$) x 107            | 16$^{+3}_{-4}$                         | 1.3$^{+0.6}_{-0.6}$        | (4.9$^{+1.4}_{-1.4}$) x 10$^{47}$ d$_{15}$ | (5.1$^{+1.6}_{-1.6}$) x 10$^{46}$ d$_{15}$ |

Table 1: Estimations of energy flux, fluence, luminosity and total energy for several models. (The Planck distribution with $kT$=175 keV is from ref. 4; the power-law distributions with exponential cut-offs at 480 keV and 800 keV are from refs. 7 and 5, respectively.)
Fig. 1.— Observed photon counts during the first 600 ms of the giant flare. \( N_{\text{MCP}} \) (red squares) and \( N_{\text{CEM}} \) (blue solid squares) show the counts of MCP and CEM instruments accumulated over a bin of 5.48 ms duration. Averages over three successive bins (16.44 ms) are taken for \( N_{\text{CEM}} \) (blue open squares) after 200 ms. Vertical error bars represent 1 \( \sigma \) statistical deviations, which become smaller than the symbol size for \( N_{\text{MCP}} > 100 \). Grey bars show the data gaps every 32 bin (or every 187.09 ms) caused by the scheduled instrumental operation. Before \( t=0 \), the photon counts were below \( \sim 11 \). The black arrow shows this upper limit. The inset shows \( t=0-60 \) ms with a linear scale.
Fig. 2.— Calibration of the $\gamma$-ray sensitivity of the MCP detector. The observed MCP counts (counts per s) are compared with the counts synthesized from the solar $\gamma$-ray photon observations with the estimated $[\epsilon S]_{\text{MCP,L}}$ and $[\epsilon S]_{\text{MCP,H}}$ for five solar $\gamma$-ray flares (Goes class X3.7 on 22 November 1998, X4.9 on 18 August 1998, X2.3 on 24 November 2000, X5.3 on 25 August 2001 and X9.4 on 6 November 1997). The blue and red parts of each bar represent contributions from the photons in the energy ranges of 50-500 keV and above 500 keV, respectively.