A giant γ-ray flare from the magnetar SGR 1806−20

D. M. Palmer[1], S. Barthelmy[2], N. Gehrels[2], R. M. Kippen[1], T. Cayton[1], C. Kouveliotou[4], D. Eichler[6], R. A. M. J. Wijers[7], P. M. Woods[5], J. Granot[8], Y. E. Lyubarsky[6], E. Ramirez-Ruiz[9], L. Barbier[2], M. Chester[10], J. Cummings[2,11], E. E. Fenimore[1], M. H. Finger[5], B. M. Gaensler[12], D. Hullinger[2], H. Krimm[2,3], C. B. Markwardt[2,13], J. A. Nousek[10], A. Parsons[2], S. Patel[5], T. Sakamoto[2,9], G. Sato[14], M. Suzuki[15] & J. Tueller[2]

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*NASA/Goddard Space Flight Center, and* [3]*Universities Space Research Association, Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[4]*NASA/Marshall Space Flight Center, and* [5]*Universities Space Research Association, NSSTC, XD-12, 320 Sparkman Dr., Huntsville, Alabama 35805, USA*
[6]*Department of Physics, Ben Gurion University, POB 653, Beer Sheva 84105, Israel*
[7]*Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, the Netherlands*
[8]*Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, PO Box 20450, MS 29, Stanford, California 94309, USA*
[9]*Institute for Advanced Study, Einstein Drive, Princeton, New Jersey 08540, USA*
[10]*Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[11]*National Research Council, 500 Fifth St., NW Washington, DC, 20001, USA*
[12]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street MS-6, Cambridge, Massachusetts 02138, USA*
[13]*University of Maryland, College Park, Maryland 20742, USA*
[14]*Institute of Space and Astronautical Science (ISAS)/JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan*
[15]*Saitama University, 55 Shimo-Okubo, Sakura-ku, Saitama City, Saitama 338-8570, Japan*

Two classes of rotating neutron stars—soft γ-ray repeaters (SGRs) and anomalous X-ray pulsars—are magnetars[1], whose X-ray emission is powered by a very strong magnetic field ($B \approx 10^{15}$ G). SGRs occasionally become 'active', producing many short X-ray bursts. Extremely rarely, an SGR emits a giant flare with a total energy about a thousand times higher than in a typical burst[2–4]. Here we report that SGR 1806−20 emitted a giant flare on 27 December 2004. The total (isotropic) flare energy is 2×10^{46} erg, which is about a hundred times higher than the other two previously observed giant flares. The energy release probably occurred during a catastrophic reconfiguration of the neutron star's magnetic field. If the event had occurred at a larger distance, but within 40 megaparsecs, it would have resembled a short, hard γ-ray burst, suggesting that flares from extragalactic SGRs may form a subclass of such bursts.

Only two other giant flares have previously been recorded, one each from SGR 0526–66 on 5 March 1979 (refs 2, 3) and SGR 1900+14 on 27 August 1998 (ref. 4). Intense X-ray burst activity from SGR 1900+14 preceded the 27 August 1998 flare[5]; no similar activity was seen preceding the 5 March 1979 event, but it may have occurred without being detected by the instruments operating at the time, given the larger distance to SGR 0526–66 in the Large Magellanic Cloud. In the year leading up to the SGR 1806−20 flare, well-sampled X-ray monitoring observations of the source with the Rossi X-ray Timing Explorer (RXTE) indicated that it was also entering a very active phase[6], emitting more frequent and intense bursts and showing enhanced persistent X-ray emission that was, indeed, a prelude to the unprecedented giant flare.

On 27 December 2004 the Swift satellite[7] was among a large number of spacecraft inundated by radiation from SGR 1806−20 (refs 8–10). The Burst Alert Telescope (BAT)[11] is a γ-ray (15–350 keV) coded aperture imager on Swift. Although Swift was turned away from the SGR location, and so the event illuminated the detector from behind, the flux that passed through the spacecraft and shielding of the BAT provided excellent measurements of the event. The BAT light curve (Fig. 1; see the Supplementary Figures for more detail) demonstrates that magnetar giant flares are remarkably similar: all three start with an initial very short and spectrally hard main spike, followed by an extended softer tail highly modulated at the neutron star's spin period. The bright, main spike lasts ~0.5 s and is followed by a tail with ~50 cycles of high-amplitude pulsations at the known rotation period of SGR 1806−20 (7.56 s). In the 27 December event we also notice a 1-s-long, flat-topped precursor burst at 142 s before the main spike.

Several astounding new properties of a magnetar flare are revealed from the superb time resolution of the BAT. Figure 1b plots the sharp initial rise of the main spike in time bins of 100 μs, equivalent to the light-crossing time of the neutron star diameter. Before the steep rise of the initial spike, the count rate was rising for 40 ms at a slower rate (shown in Supplementary Fig. 2) and had reached roughly 30,000 c.p.s. (above a ~9,000 c.p.s. background) by $t = 0$. At that point it increased by a factor of more than 100 in less than 1.5 ms, rising with a 0.3 ms exponential time constant. This is followed by at least one dip and continued brightening (additional dips would not be visible owing to instrument saturation) on its way to the peak. The flare rise has thus been resolved for the first time. The flux during the spike, though heavily attenuated, saturated the BAT modules, precluding a reliable flux measurement. We have therefore used the SOPA[12] and ESP[13] instruments located on geosynchronous satellites (see the Supplementary Methods) to measure the main peak flux. The SOPA instruments are small silicon detectors designed with fast event processing to measure the high particle fluxes found in orbit. During the peak of the burst, each detector had a deadtime greater than 50%, but this level of saturation can be accurately corrected for. We fitted the SOPA data with an exponential-cutoff power law (finding a characteristic temperature $kT = 0.48(4)$ MeV and a power-law photon index $-0.2(1)$) and derive a flux of $5.0(3)\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ over an 0.160 s integration time for 45 keV to 10 MeV photons; the corresponding fluence is $0.80(5)\,\mathrm{erg\,cm^{-2}}$. (Here the number in parentheses indicates the uncertainty in the value given.) This duration and spectral hardness is in the range of characteristics found for the short, hard subclass of classic γ-ray bursts (GRBs)[14].

Because the count rate was significantly lower during the tail, we were able to model the off-axis illumination and calibrate the flux and spectroscopy measurements (see Supplementary Methods). We find the tail of the burst to have an energy fluence of $1.0(5) \times 10^{-3}\,\mathrm{erg\,cm^{-2}}$ at photon energies >60 keV. The spectral fits are consistent with thermalized spectra with $kT \approx 15$–30 keV as seen in previous flares, implying a comparable energy fluence below our 60-keV threshold. Accounting for the 10–60-keV photons, we project the total tail fluence to be $\gtrsim 2 \times 10^{-3}\,\mathrm{erg\,cm^{-2}}$, roughly 0.3% that of the main peak. For a distance to SGR 1806−20 of $15d_{15}$ kpc (ref. 15), we then find an (isotropic equivalent) energy release of $2\times10^{46}d_{15}^2$ erg in the spike, and $5\times10^{43}d_{15}^2$ erg in the tail. (Here, $d_{15} = d/(15\,\mathrm{kpc})$; similarly $E_{46} = E/(10^{46}\,\mathrm{erg})$ and $V_{18} = V/(10^{18}\,\mathrm{cm}^2)$.) Thus, the isotropic equivalent energy in the initial spike is about two orders of magnitude larger than that in the other two giant flares, while the energy in the tail is comparable. Indeed, a radio afterglow[16] was detected from this flare with a luminosity 500 times that from the 27 August flare, suggesting a very large difference in the prompt burst energy. The consistency of the tail energies among the three flares is attributable to the fact that they are limited by the storage capacity of the magnetic field[1,17] and should be as constant from source to source as the field energy. Thus, the tail luminosities, which are expected to be at roughly the magnetically modified Eddington limit, should also be similar, as observed. The extent of magnetic reconnection, on the other hand, governs the prompt energy release during the main spike; this can vary greatly from one event to the next, even within the same source.

The pulse profile in the tail of the flare just after the main spike features one large peak and two smaller adjacent local maxima separated by about a quarter of a rotation cycle (Fig. 2 and Supplementary Fig. 1). The relative intensities of the peaks change during the tail, but their phases remain fixed, indicating that the field configuration does not change substantially during the tail and that the released energy comes from the trapped fireball.

The polar B field of SGR 1806$-$20 has been calculated[18] from its spin-down rate to be $\sim 1.6 \times 10^{15}$ G, corresponding to a external magnetic field energy of 2×10^{47} erg, which indicated that at most $10 d_{15}^{-2}/f$ such giant flares can be produced from the star in its lifetime (here f is the beaming factor).

We used RXTE to measure the spin frequency and spin-down rate of the SGR 30 days after the flare[19]. The frequency is consistent with an extrapolation of the pre-flare frequency with pre- and post-flare spin-down rates. Thus, the 27 December flare could not have caused a rapid, lasting change in the spin frequency greater than $\sim 2 \times 10^{-5}$ Hz; this, despite the much larger apparent burst energy, limits the frequency change to be at most comparable to that seen following the 27 August flare[20]. The post-flare spin-down rate, $-3.15(9) \times 10^{-12}$ Hz s^{-1}, although lower than it was shortly before the flare, is still in its historical range.

The three timescales in the phenomenon—(1) the rise time of $\sim$1 ms, (2) the duration of the hard spike of $\sim$0.5 s, and (3) the duration of the tail of several minutes—are similar for all three giant flares. These are attributed to the Alfvén propagation times in (1) the magnetosphere and (2) the star, and (3) the cooling time of the trapped pair fireball, respectively[1,17].

Violent energy dissipation can occur anywhere in the magnetically dominated region, which includes the outer layers of the neutron star: if an energy of $10^{46} E_{46}$ erg is dissipated roughly uniformly in the reconnection region of volume $10^{18} V_{18}\,\mathrm{cm}^3$, then matter above the layer at a density of $10^8 E_{46}/V_{18}\,\mathrm{g\,cm^{-3}}$ will have an energy density larger than its gravitational potential and become unbound. This is about 10^{24} g, which can be ejected into the magnetosphere at fractions of the speed of light, c. Such a mass ejection (which need not be isotropic) is enough to power the observed radio nebula and its $0.3c$ expansion[16].

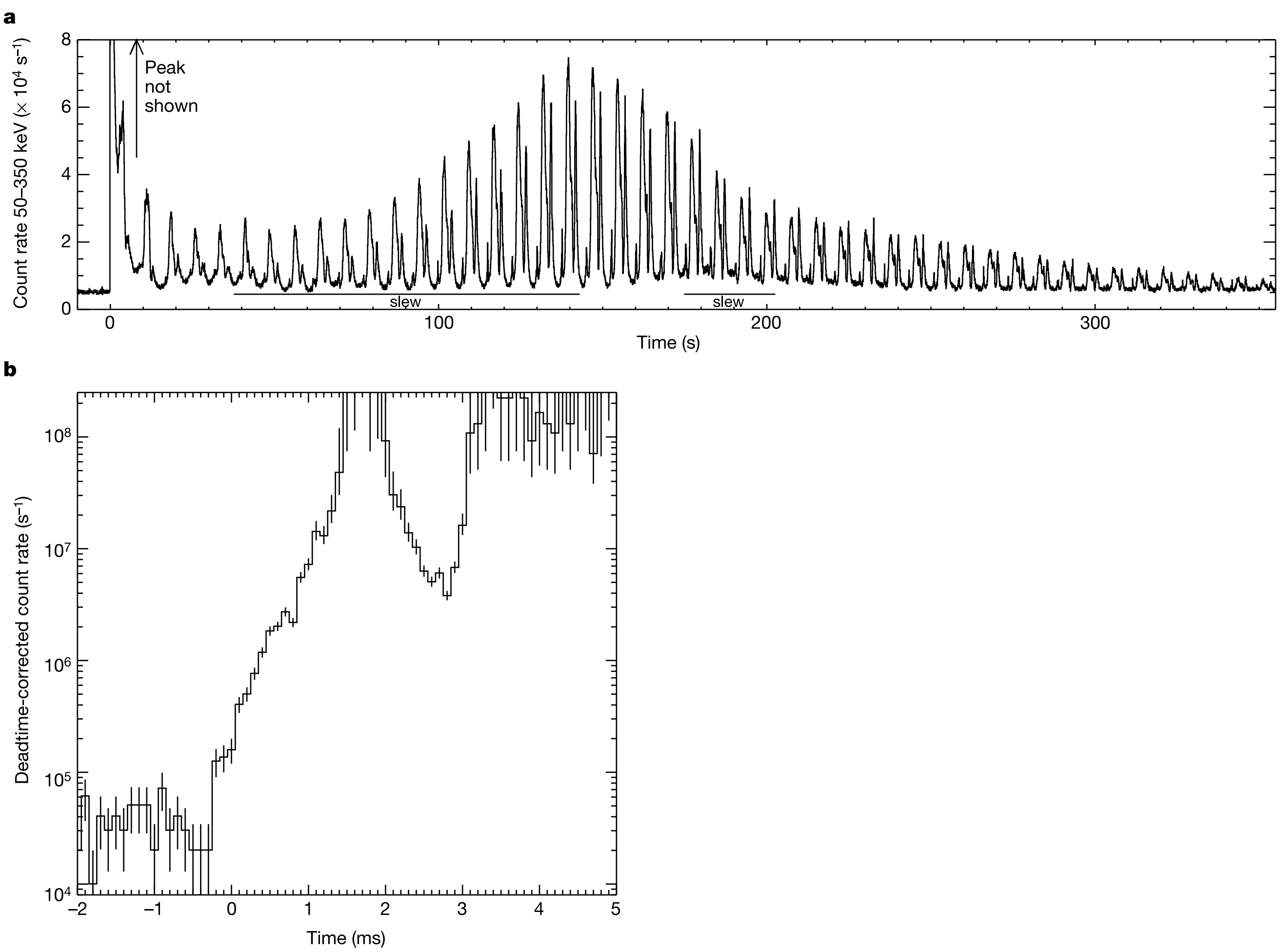

Figure 1 The SGR spike and tail light curve from BAT on Swift. **a**, BAT count rate at measured energy >50 keV (64-ms bins). Although BAT was pointed 105° away from the SGR at the time of the main spike, it recorded γ-rays above 60 keV passing through and scattering within the spacecraft body and instrument shielding. As part of a pre-planned observing schedule, Swift slewed to observe a different source shortly after the main peak, reaching a steady pointing direction 61° from the SGR at 143 s. The spacecraft reorientation improved the detection efficiency of the SGR, visible as an apparent (not intrinsic) rise in the light curve to a peak at 140 s. This is followed by a second slew to 67°. **b**, BAT deadtime-corrected count rate (all energies) during the complex leading edge of the main spike. (Note that the horizontal scale is 10^4 times larger than in **a**.) Uncertainties in the deadtime correction (discussed in the Supplementary Methods) make corrected count rates increasingly unreliable above 5×10^7 counts per second. Error bars combine 1 s.d. counting statistics and the deadtime uncertainty. Time bins of 100 μs are equivalent to the light-crossing-time of a neutron star diameter. More detailed lightcurves are shown in the Supplementary Figures.

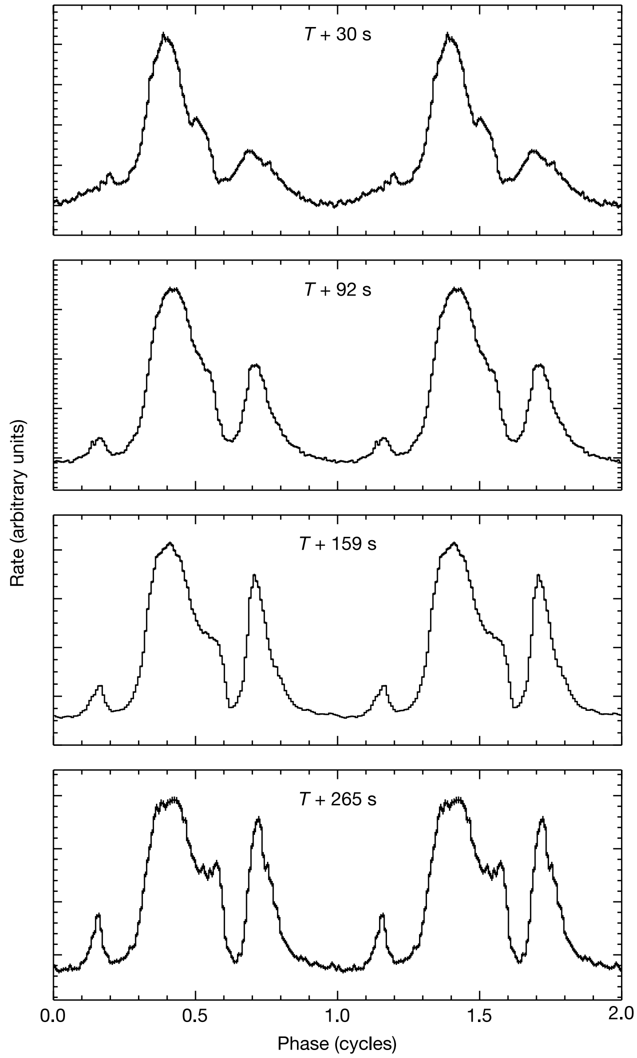

Figure 2 The pulse profile evolution of the magnetar SGR 1806–20 during the giant flare of 27 December 2004. Time through the flare increases from top to bottom. Each panel displays the pulse profile folded over four pulse cycles at one of four different time intervals during the flare. The times denoted at the top of each panel indicate the midpoint of the interval relative to the start of the main spike. During the first half of the tail (~170 s), the peak centred at phase 0.7 grows in amplitude as the primary peak fades until the two are nearly equal in height. Thereafter, the two peaks decay in lockstep while the relative amplitude of the third peak at phase 0.2 increases. Overall, the pulse profile becomes less sinusoidal during the course of the flare, that is, the power in the higher harmonics increases relative to the power at the fundamental frequency, opposite to what was seen in SGR 1900+14 during the 27 August flare[24]. The phases of the SGR 1806–20 pulse peaks remain fixed, indicating a finalized magnetic geometry, and supporting the notion that after the first spike no new magnetic energy is released, and only the trapped fireball energy leaks out. The individual pulses throughout the tail can be seen in Supplementary Fig. 1.

The two earlier flares would have been detectable by existing instruments only within ~8 Mpc, and it was therefore not previously thought that such flares could be the source of the short, hard GRBs. The main spike of the 27 December giant flare would have resembled a short, hard GRB had it occurred within $40d_{15}$ Mpc, encompassing even the Virgo cluster. Magnetar formation rate is expected to follow the star formation rate, which is (for $z = 0$) $1.3 \pm 0.2 M_{\odot}\,\mathrm{yr}^{-1}$ in our Galaxy[21] and $0.013^{+0.02}_{-0.007} M_{\odot}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ averaged over intergalactic scales[22]. This suggests that the Burst And Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory would have triggered on such events as short GRBs at a rate of $N_{\mathrm{BATSE}} = 80(\dot{N}_{\mathrm{gal,GF}}/0.03\,\mathrm{yr}^{-1})d_{15}^{3}\,\mathrm{yr}^{-1}$, to be compared to an estimate of the 4π sr BATSE rate of about $150\,\mathrm{yr}^{-1}$. Here, $\dot{N}_{\mathrm{gal,GF}}$ is the average rate of giant flares in the Galaxy similar to the 27 December event. The observed isotropic distribution of short BATSE GRBs on the sky and the lack of excess events from the direction of the Virgo cluster suggests that only a small fraction ($\lesssim 0.05$) of these events can be SGR giant flares within $\lesssim 40$ Mpc. This implies either that $d \lesssim 7$ kpc, $N_{\mathrm{gal,GF}} \lesssim 3 \times 10^{-3}\,\mathrm{yr}^{-1}$ on average for a Galaxy like our own, or that the luminosity distribution includes even larger SGR flares that can be seen at a greater distance[23]. One possible distinction of these from the classic GRB population may well come from their radio observations, because their radio afterglows should not be detectable beyond ~1 Mpc. The fraction of SGR events among what are now classified as short GRBs may not be predominant, but it should be detectable. This will be testable with future Swift observations. □

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Correspondence and requests for materials should be addressed to D.M.P. (palmer@lanl.gov).