A giant periodic flare from the soft γ-ray repeater SGR1900+14

K. Hurley*, T. Cline†, E. Mazets‡, S. Barthelmy†, P. Butterworth†, F. Marshall†, D. Palmer†, R. Aptekar‡, S. Golenetskii‡, V. Il'Inskii‡, D. Frederiks‡, J. McTiernan*, R. Gold§ & J. Trombka†

** UC Berkeley Space Sciences Laboratory, Berkeley, California 94720-7450, USA*
† NASA Goddard Space Flight Center, Code 661, Greenbelt, Maryland 20771, USA
‡ Ioffe Physical-Technical Institute, St Petersburg 194021, Russia
§ The Johns Hopkins University, Applied Physics Laboratory, Laurel, Maryland 20723, USA

Soft γ-ray repeaters are transient sources of high-energy photons; they emit sporadic and short (about 0.1 s) bursts of 'soft' γ-rays during periods of activity, which are often broken by long stretches of quiescence. These objects are associated with neutron stars in young supernova remnants[1]. The event of 5 March 1979 was the most intense burst to date, and the only one that showed a clear periodicity in the signal[2,3]. Here we report the detection, on 27 August 1998, of an even more intense burst from a different soft γ-ray repeater. This event was characterized by 'hard' γ-rays at its peak, followed by a tail 300 s long with a soft spectrum and a clear periodicity of 5.16 s. The burst was probably initiated by a massive disruption of the crust of the neutron star, followed by an outflow of energetic particles rotating with the period of the star. A comparison of the events of 27 August 1998 and 5 March 1979 supports the idea that magnetic energy plays an important role in the genesis of such events. Although these giant flares are rare, they are not unique events and may occur at any time in a neutron star's activity cycle.

Four soft γ-ray repeaters (SGRs) are known. All appear to be associated with radio supernova remnants, indicating that they are young[4] ($<$20,000 yr). SGRs are probably strongly magnetized neutron stars ('magnetars'[5]), in which, unlike the radio pulsars, the magnetic energy dominates the rotational energy. SGR0525-66 produced the unusual, energetic and periodic burst of 5 March 1979 (refs 3, 6, 7) and a series of subsequent, much smaller bursts[8,9]. It lies towards the N49 supernova remnant in the Large Magellanic Cloud[10,11]. A quiescent soft X-ray source has been identified that may be the neutron star[12]. SGR1900+14, first detected in 1979, was, until recently, the least prolific SGR[13,14], hindering attempts to locate it precisely. Several lines of evidence suggested that it was associated with the Galactic supernova remnant G42.8+0.6 (ref. 15) and a quiescent soft X-ray source[16]. This possible association was strengthened by a source location obtained with the network synthesis method[17], and more recently by triangulation[18–20], although because this X-ray source lies outside the remnant, the connection between the two could still be considered to be unresolved.

An observation of the quiescent soft X-ray source possibly associated with SGR1900+14 by the ASCA spacecraft in April 1998 showed that the X-rays exhibited a 5.16-s period[21]. In May of that year, SGR1900+14 came out of a long dormant phase, emitting strong, frequent bursts[18,22]. On 27 August 1998, it emitted the exceptionally intense giant flare reported here, detected by instruments on the GGS-Wind[23], Ulysses[20], Rossi X-Ray timing Explorer[24] (RXTE), Beppo SAX, and Near Earth Asteroid Rendezvous (NEAR) spacecraft. The entire event profile is shown in Fig. 1 with Ulysses data at 0.5 s resolution. In very general terms, the burst rose to a maximum and decayed roughly as a power law in time with an index of about -1.8. However, the event onset is complex; Konus-Wind observations (Konus is an experiment aboard the GGS-Wind spacecraft) resolve components $<$4 ms long. A sinusoidal component dramatically modulated the later part of the profile with varying amplitudes for the duration of the observation, the first direct detection of the 5.16-s periodicity at hard X-ray energies. Figure 1, inset, shows Ulysses data with 31.25-ms time resolution, demonstrating that the 5.16-s pulsations commenced ~35 s after the peak. It is clear that the pulse profile is considerably more complex than a single sinusoidal curve, with at least four maxima and minima in a single cycle.

A remarkable coincidence—the initiation of NEAR γ-ray monitoring only days before 27 August but after many months of silent cruise towards Eros—made possible the high-precision source localization of this event by triangulation; this was done by analysis of the arrival times at Ulysses, GGS-Wind, RXTE and NEAR. This is the only time, other than for the 5 March 1979 event[10,11], that an SGR has been localized by triangulation at three or more widely separated spacecraft, leading directly to an error box. All six source error annuli determined from the various two-spacecraft comparisons, are consistent with the coordinates of the quiescent soft X-ray source[17,20] (J2000 right ascension 19 h 0.7 min 14 s, declination 9° 19′ 19″). The details will be reported elsewhere, but we note that this positional agreement, as well as the agreement between the periodicities found in soft X-rays and in the giant-flare light curve, now leave no doubt about the association between the SGR and the quiescent X-ray source.

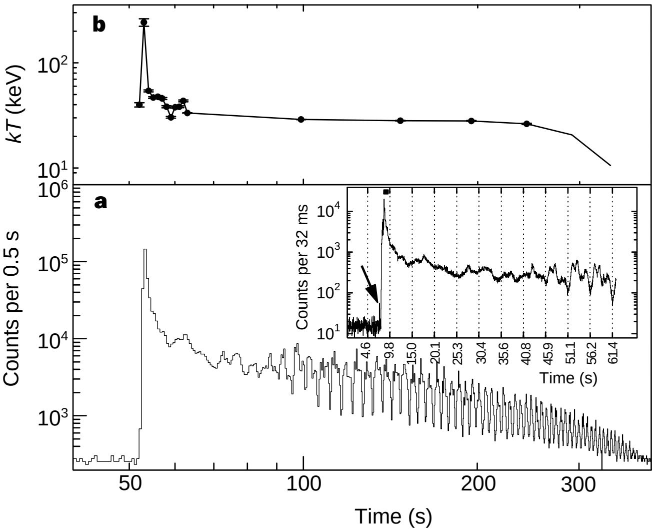

Figure 1 Ulysses data for the 27 August 1998 giant flare. **a**, 25–150 keV time history, corrected for dead-time effects, from the 0.5-s resolution continuously available real-time data. Zero seconds corresponds to 37,283.12s UT at Earth. This event was so intense that it temporarily saturated or shut down some experiments, but because of the relatively small detection area of the Ulysses[28] sensor (20 cm^2), it was not subject to severe dead-time or pulse pile-up problems; in fact solar flare data producing considerably higher count rates have been successfully analyzed with this instrument. Inset, 0.03125-s-resolution time history of the event from the triggered data, available for 64 s. The burst triggered on the precursor (arrow) ~0.4 s before the main peak. A grid is drawn to indicate the 5.16-s periodicity, showing its absence for the first ~35 s after the main peak. The short horizontal line at the top indicates the position of the hard spectral peak measured by Ulysses. Zero seconds corresponds to 37,327.81 s UT at Earth. **b**, Spectral temperature as a function of time. The spectra were measured by Ulysses in intervals with increasing durations of 1–48 s. No simple, two-parameter fit describes the spectrum well, in part because the measurement uncertainties are dominated by systematic effects. However, we have used an optically thin thermal bremsstrahlung spectrum to characterize approximately the spectral temperature.

Table 1 Comparison of the two bursts

Property	Burst	
	27 August 1998	5 March 1979
Rise time	Complex, structures <4 ms	Simple, <2 ms
Morphology of main peak	Complex structure, duration ~1 s	Complex structure duration ~150 ms[26]
Periodicity	5.16 s	8.1 s
Peak flux (erg cm^{-2} s^{-1})	⩾3.4×10^{-3}, >25 keV	~1.5×10^{-3}, >50 keV
Fluence (erg cm^{-2})	⩾7×10^{-3}	~2×10^{-3}
Spectrum at peak, kT (keV)	240 (average over 1 s)	246 (average over 200 ms)[27]
Highest photon energy in peak	2 MeV	>1 MeV
Spectrum of pulsations, kT (keV)	30	30
Source distance (kpc)	~7 (G42.8+0.6)	~50 (N49)
Peak source luminosity (erg s^{-1})	⩾2×10^{43}	~5×10^{44}
Precursor observed?	Yes	No
Delay between main peak and periodic emission	35 s	None
Ratio of energy in main peak to total energy in burst	0.46	0.25
Source activity in months preceding the burst	Intense	None observed

The temperature of the energy spectrum of this event is shown in Fig. 1. With the exception of the peak, the temperature is $kT \approx 30$ keV, which is similar to SGR bursts in general. At the peak, however, the temperature averaged over a 1-s interval is $kT \approx 240$ keV. Measurements with finer time resolution were recorded by Konus-Wind, indicating a peak temperature of ~1,200 keV, and a maximum photon energy of 2 MeV. Hard spectra such as these are not characteristic of SGR bursts; one was observed for the peak of the 5 March 1979 event[6,25]. Table 1 compares the properties of these two giant flares.

Comparisons between very intense bursts observed by different instruments are subject to numerous uncertainties. Dead-time effects, different time resolutions and energy ranges, and pulse pile-up are difficult or even impossible to correct for; hence the 'approximate' and 'greater than' symbols in Table 1. However, within these uncertainties, the parameters of the 27 August 1998 event are consistent with its having the largest peak flux and fluence of any of the several thousand SGRs and cosmic γ-ray bursts observed to date.

It has been suggested recently[22,25] that the neutron stars associated with SGRs are magnetars, that is, that they have magnetic fields of several times 10^{14} G (ref. 5). This is based on observations of the quiescent counterparts in X-rays, which display pulsations with a slowly lengthening period; the spindown is interpreted as being due to magnetic dipole radiation. In the magnetar model, the giant flares of 27 August and 5 March are due to a readjustment of the magnetic field, accompanied by a massive, large-scale cracking of the neutron-star crust. In both cases, the initial hard spectrum would be produced by the conversion of magnetic energy to energy in a clean electron–positron and photon fireball uncontaminated by ions, which would soften the spectrum. The highest-energy photons observed are only slightly above the electron–positron pair production threshold; this is consistent with attenuation due to this process, although there is at present no direct evidence for a cutoff. Expanding away from the stellar surface, part of the fireball would be trapped in the magnetosphere, producing the observed soft-spectrum tails. The periodicity indicates that this emission was either anisotropic and/or that it occurred close enough to the neutron star to be occulted by it; the decay in intensity with approximately constant spectral temperature is interpreted as a shrinking in the volume of the emission region. The complex pulse structure implies that several regions of the magnetosphere were involved. We note that, despite the factor of 25 difference between the peak luminosities of the 27 August and 5 March events, the ratios of peak to total energy are within a factor of 2 of each other, suggesting that similar magnetic field geometries may be important. As the soft spectrum that follows the intense main peak in both cases is attributed to radiation from an optically thick pair plasma trapped in the neutron star's magnetosphere, the magnetic field strength may be estimated from the energy in this component[5]:

$$B > 4 \times 10^{14}\left(\frac{\Delta R}{10\,\mathrm{km}}\right)^{-3/2}\left(\frac{1+\Delta R/R}{2}\right)^{3}\left(\frac{E_{\mathrm{tail}}}{3.6 \times 10^{44}\,\mathrm{erg}}\right)^{1/2}\mathrm{G}$$

where R is the radius of the neutron star and ΔR (~10 km) is the outer radius of the magnetic flux loop containing the pair plasma. For the 5 March event, this gives $B > 4 \times 10^{14}$ G; for the 27 August event, $B > 10^{14}$ G, providing a confirmation of the magnetar model which is independent of the observation and interpretation of the spindown, but consistent with it.

The existence of a strong magnetic field helps to explain the high luminosities encountered in both events, five to six orders of magnitude greater than the Eddington limit. A strong magnetic field suppresses the Compton scattering cross-section, and reduces the opacity[5].

The giant flare of 5 March 1979 was observed to precede the much smaller event series from SGR0525−66. Observations during the preceding six months failed to reveal any source activity, and it was speculated at the time that this was a unique, catastrophic event in the life of a neutron star, and one that initiated the series of bursts subsequently observed. Our observation of the 27 August 1998 event leads to a different interpretation. The source evolved from a weak, infrequent repeater to an intensely active one, indicating that the neutron star's crust was able to adjust to magnetic stresses by undergoing relatively minor, localized cracking for a long period. The small precursor to the giant flare was comparable in intensity to these bursts, and may have been the final trigger for it. In the following months, these bursts have continued. Thus our observations imply that rare giant flares on SGRs may be the rule, rather than the exception, and that they may occur at any time. It therefore seems likely that SGR0525−66 had emitted relatively weak bursts before 5 March 1979, and that these bursts were not detected owing to their weakness or, perhaps, spacecraft coverage. The magnetar theory predicts that on any given SGR, such events may recur on a timescale of decades or more (R. Duncan, personal communication): as it is now almost two decades since the 5 March event, future monitoring of this and other SGRs could confirm this idea.

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Correspondence and requests for materials should be addressed to K.H. (e-mail: khurley@sunspot.ssl.verkeleg.edu).

Reversing the direction of the supercurrent in a controllable Josephson junction

J. J. A. Baselmans*, A. F. Morpurgo*†, B. J. van Wees* & T. M. Klapwijk*

* *Department of Applied Physics and Material Science Center, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

When two superconductors are connected by a weak link, a supercurrent flows, the magnitude of which is determined by the difference in the macroscopic quantum phases of the superconductors. This phenomenon was discovered by Josephson[1] for the case of a weak link formed by a thin tunnel barrier: the supercurrent, I, is related to the phase difference, ϕ, through the Josephson current–phase relation, $I = I_c \sin\phi$, with I_c being the critical current which depends on the properties of the weak link. A similar relation holds for weak links consisting of a normal metal, a semiconductor or a constriction[2]. In all cases, the phase difference is zero when no supercurrent flows through the junction, and increases monotonically with increasing supercurrent until the critical current is reached. Here we use nanolithography techniques to fabricate a Josephson junction with a normal-metal weak link in which we have direct access to the microscopic current-carrying electronic states inside the link. We find that the fundamental Josephson relation can be changed from $I = I_c \sin\phi$ to $I = I_c \sin(\phi + \pi)$—that is, a π-junction—by controlling the energy distribution of the current-carrying states in the normal metal. This fundamental change in the way these Josephson junctions behave has potential implications for their use in superconducting electronics as well as in (quantum) logic circuits based on superconductors.

The microscopic mechanism responsible for the supercurrent in a Josephson junction is the transport of correlated electrons. In a superconductor/normal-metal/superconductor (SNS) junction, conduction electrons mediate current transport from superconductor 1 (S1) to superconductor 2 (S2) by either ballistic or diffusive transport through the normal metal (N). In a ballistic junction, in which the elastic mean free path is larger than the length of the normal region, Andreev bound states are formed[3–5]. The dispersion relation of these states is such that each subsequent state carries a supercurrent in the positive or negative direction at a given value of the macroscopic phase difference between the superconductors; the states are degenerate if the phase is zero. The net supercurrent that flows between the two superconductors depends therefore not only on the actual phase difference ϕ, but also on the occupation of the Andreev bound states. The prediction is that the electron energy distribution function in the normal region will change the supercurrent, even resulting in a sign reversal[6–8].

Transport of electrons in metals is usually diffusive, the electron trajectories are not well defined, and Andreev bound states are no longer the natural concept to describe the supercurrent. But electron correlations induced by the superconducting electrodes are still present, with the energy scale determined by the Thouless energy $E_T = \hbar D/L^2$, where D is the diffusion coefficient and L is the separation between the superconductors. The energy spectrum of the superconducting correlations is expressed in a so-called supercurrent-carrying density of states, which can be calculated directly using the quasiclassical Green's function theory of superconductivity[9–12]. The supercurrent-carrying density of states is an odd function of energy; it shows a phase-dependent mini-gap at low energies, above which it has a positive maximum, after which it changes sign and approaches zero at high energies. The positive and negative

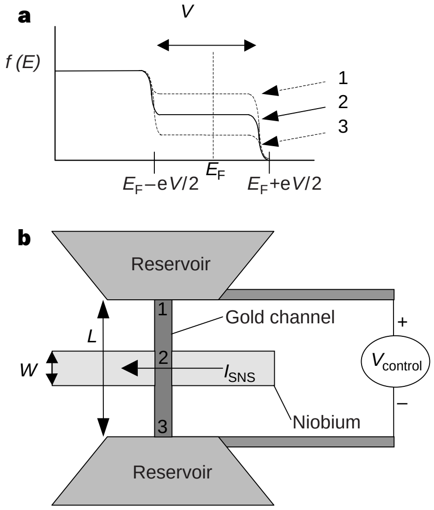

Figure 1 Electronic distribution function and the sample layout. In the bottom panel, a gold channel between two electron reservoirs is connected to two niobium superconducting leads. The control voltage across the channel induces a position-dependent electron distribution, shown in **a** for positions 1, 2 and 3 in **b**. The current through the Josephson junction is indicated by I_{SNS}.

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† Present address: Department of Physics, Stanford University, Stanford, California 94305-4060, USA.