A giant, periodic flare from the soft gamma repeater SGR1900+14

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Soft gamma repeaters are high-energy transient sources associated with neutron stars in young supernova remnants\textsuperscript{1}. They emit sporadic, short (\(\sim 0.1\) s) bursts with soft energy spectra during periods of intense activity. The event of March 5, 1979 was the most intense and the only clearly periodic one to date\textsuperscript{2,7}. Here we report on an even more intense burst on August 27, 1998, from a different soft gamma repeater, which displayed a hard energy spectrum at its peak, and was followed by a \(\sim 300\) s long tail with a soft energy spectrum and a dramatic 5.16 s period. Its peak and time integrated energy fluxes at Earth are the largest yet observed from any cosmic source. This event was probably initiated by a massive disruption of the neutron star crust, followed by an outflow of energetic particles rotating with the period of the star. Comparison of these two bursts supports the idea that magnetic energy plays an important role, and that such giant flares, while rare, are not unique, and may occur at any time in the neutron star’s activity cycle.

Four soft gamma repeaters (SGRs) are known. All appear to be associated with radio supernova remnants, indicating that they are young\textsuperscript{4} (<20,000 y). SGRs are probably strongly magnetized neutron stars (’magnetars’\textsuperscript{5}), in which, unlike the radio pulsars, the magnetic energy dominates the rotational energy. SGR0525-66 produced both the unusual, energetic and periodic burst of March 5 1979\textsuperscript{6,7,8} and a series of subsequent, much smaller bursts\textsuperscript{9,10}. It lies towards the N49 supernova remnant in the Large Magellanic Cloud\textsuperscript{11,12}. A quiescent soft X-ray source has been identified which may be the neutron star\textsuperscript{13}. SGR1900+14, first detected in 1979, was, until recently, the least prolific SGR\textsuperscript{14,15}, hindering attempts to locate it precisely. Several lines of evidence suggested that it was associated with the galactic supernova remnant G42.8+0.6\textsuperscript{16} and a quiescent soft X-ray source\textsuperscript{17}. This possible association was strengthened by a source location obtained with the network synthesis method\textsuperscript{18}, and more recently by triangulation\textsuperscript{19,20,21}, although since 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. In May, SGR1900+14 came out of a long dormant phase, emitting strong, frequent bursts. On August 27, it emitted the exceptionally intense giant flare reported here, detected by instruments on GGS-Wind, Ulysses, the Rossi X-Ray Timing Explorer (RXTE), BeppoSAX, and the Near Earth Asteroid Rendezvous (NEAR). The entire event profile is shown in figure 1 with Ulysses 0.5 s resolution data. In very general terms, the burst rose to a maximum and decayed roughly as a power law in time with an index of $\sim -1.8$. However, the event onset is complex; Konus-Wind observations resolve components $<4$ ms. A sinusoidal component dramatically modulated the later part of the profile for the duration of the observation with varying amplitudes, the first direct detection of the 5.16 s periodicity at hard X-ray energies. The inset to Figure 1 shows 31.25 ms time resolution Ulysses data, demonstrating that the 5.16 s pulsations commenced approximately 35 s after the peak. It is clear that the pulse profile is considerably more complex than a single sinusoidal curve, with at least 4 maxima and minima in a single cycle.

A remarkable coincidence, the initiation of NEAR gamma-ray monitoring only days before August 27th but after many months of silent cruise towards Eros, made possible the high-precision source localization of this event by triangulation, i.e., analysis of the arrival times at Ulysses, GGS-Wind, RXTE, and NEAR. This is the only time, other than for the March 5, 1979 event, that an SGR has been localized by triangulation at three or more widely separated spacecraft, leading directly to an error box. All six source annuli, determined from the various two-spacecraft comparisons, are consistent with the coordinates of the quiescent soft X-ray source (RA(J2000) = 19 h 07 m 14 s, Dec(J2000) = 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.

The temperature of the energy spectrum of this event is shown in figure 1. With the exception of the peak, the temperature is $kT \sim 30$ keV, which is similar to SGR bursts in general. At the peak, however, the temperature averaged over a 1 s interval is $kT \sim 240$ keV. Finer time resolution measurements were recorded by Konus, indicating a peak temperature $\sim 1200$ 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 March 5 1979 event. 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, to within these uncertainties, the parameters of the August 27 1998 event are consistent with it having the largest peak flux and fluence of any of the several thousand SGRs and cosmic gamma-ray bursts observed to date.

Recently it has been suggested that the neutron stars associated with SGRs are magnetars, i.e. that they have magnetic fields of several times $10^{14}$ G. This is based on observations of the
quiescent counterparts in X-rays, which display pulsations with a slowly lengthening period; the spin-down is interpreted as due to magnetic dipole radiation. In the magnetar model, the giant flares of August 27 and March 5 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 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. It is noteworthy that, despite the factor of 25 difference between the peak luminosities of the August 27 and March 5 events, the ratios of peak to total energy are within a factor of 2 of each other, suggesting that similar magnetic field geometries may play an important role. Since the soft spectrum which 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:

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

Where \( R \) is the radius of the neutron star and \( \Delta R \) (\( \sim \)10 km) is the outer radius of the magnetic flux loop containing the pair plasma. For the March 5 event, this gives \( B > 4 \times 10^{14} G \); for August 27, \( B > 10^{14} G \), providing a confirmation of the magnetar model which is independent of the observation and interpretation of the spin-down, 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.

The giant flare of March 5 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 August 27 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 emitted relatively
weak bursts prior to March 5, 1979, which went undetected due to spacecraft coverage and/or weakness. The magnetar theory predicts that on any given SGR, such events may recur on a timescale of $\sim$decades or more\textsuperscript{28}. It is now almost two decades since the March 5 event; future monitoring of this and other SGRs can confirm this idea.

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Table 1. Properties of the August 27 1998 and March 5 1979 bursts

|                          | August 27 1998                        | March 5 1979                        |
|--------------------------|--------------------------------------|-----------------------------------|
| Rise time                | Complex, structures <4 ms            | Simple, <2 ms                     |
| Morphology of main peak  | Complex structure, duration ~1 s     | Complex structure, duration ~150 ms^{30} |
| Periodicity              | 5.16 s                               | 8.1 s                             |
| Peak flux, erg cm^{-2} s^{-1} | ≥ 3.4x10^{-3} , > 25 keV            | ~1.5x10^{-3} , > 50 keV           |
| Fluence, erg cm^{-2}     | ≥ 7x10^{-3}                          | ~2x10^{-3}                        |
| Spectrum at peak, kT (keV) | 240 (average over 1 s)               | 246 (average over 200 ms)^{26}    |
| 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 | ≥ 2x10^{43}                        | ~5x10^{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                     |
Figure 1. Ulysses data for the August 27 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 37283.12 s 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 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.

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 grossly the spectral temperature.

c. 0.03125 s resolution time history of the event from the triggered data, available for 64 s. The burst triggered on the precursor (arrow) $\sim$0.4 s prior to the main peak. A grid is drawn to indicate the 5.16 s periodicity, showing its absence for the first $\sim$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 37327.81 s UT at Earth.
