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STATISTICAL PROPERTIES OF SGR 1900+14 BURSTS

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ABSTRACT

We study the statistics of soft gamma repeater (SGR) bursts using a database of 187 events detected with BATSE and 837 events detected with the *Rossi X-Ray Timing Explorer* Proportional Counter Array; all events are from SGR 1900+14 during its 1998–1999 active phase. We find that the fluence or energy distribution of bursts is consistent with a power law of index 1.66, over 4 orders of magnitude. This scale-free distribution resembles the Gutenberg-Richter law for earthquakes and gives evidence for self-organized criticality in SGRs. The distribution of time intervals between successive bursts from SGR 1900+14 is consistent with a lognormal distribution. There is no correlation between burst intensity and the waiting times till the next burst, but there is some evidence for a correlation between burst intensity and the time elapsed since the previous burst. We also find a correlation between the duration and the energy of the bursts, but with significant scatter. In all these statistical properties, SGR bursts resemble earthquakes and solar flares more closely than they resemble any known accretion-powered or nuclear-powered phenomena. Thus, our analysis lends support to the hypothesis that the energy source for SGR bursts is internal to the neutron star and plausibly magnetic.

Subject headings: gamma rays: bursts — stars: individual (SGR 1900+14) — X-rays: bursts

1. INTRODUCTION

At least three of the four currently known soft gamma repeaters (SGRs) are associated with slowly rotating, extremely magnetized neutron stars located within young supernova remnants (Kouveliotou et al. 1998, 1999). They are characterized by the recurrent emission of gamma-ray bursts with relatively soft spectra (resembling optically thin thermal bremsstrahlung at $kT \sim 20$–40 keV) and short durations (∼0.1 s; Kouveliotou 1995). Thompson & Duncan (1995) suggested that these bursts are due to neutron star crust fractures driven by the stress of an evolving, ultrastrong magnetic field, $B \gtrsim 10^{14}$ G.

Cheng et al. (1996) observed that particular statistical properties of a sample of 111 SGR events from SGR 1806−20 are quite similar to those of earthquakes (EQs). These properties include the distribution of event energies, which follow a power law $dN \propto E^{-\gamma}\, dE$ with an exponent, $\gamma = 1.6$. A similar distribution was obtained empirically by Gutenberg & Richter (1956a, 1965, p.16) for the distribution of EQ energies (with a power-law index of $\gamma_{\rm EQ} = 1.6 \pm 0.2$) and in computer simulations of fractures in a stressed, elastic medium (Katz 1986). The distribution of time intervals between successive SGR 1806−20 events is well described by a lognormal distribution analogous to the waiting-time distribution of microglitches seen in the Vela pulsar (see Hurley et al. 1994). Cheng et al. (1996) also show that cumulative waiting-time distributions of SGR 1806−20 and EQ events are similar. These results support the idea that SGR bursts are caused by starquakes, which are expected to occur in the crusts of magnetically powered neutron stars or "magnetars" (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996).

In 1998 May, SGR 1900+14 became extremely active after a long period during which only sporadic activity occurred (Kouveliotou et al. 1993). In the period from 1998 May until 1999 January, a total of 200 events were detected (Woods et al. 1999a) with the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma Ray Observatory* (*CGRO*). Out of these 200 events, 63 led to an on-board trigger. The sudden change in source activity initiated a series of *Rossi X-Ray Timing Explorer* (*RXTE*) observations between 1998 May 31 and December 21. During these observations, 837 bursts from SGR 1900+14 were detected with the Proportional Counter Array (PCA). As noted by Kouveliotou et al. (1998) for SGR 1806−20, the bursts occur in an apparently irregular temporal pattern. This is also true for SGR 1900+14 bursts.[7]

In this Letter, we study the statistics of SGR bursting using the new measurements of SGR 1900+14. Our database of events is larger by ∼10 than that of previous statistical studies and extends over a larger dynamic range in burst energy (or fluence) by $\sim 10^2$.

2. BATSE OBSERVATIONS

The BATSE instrument is made up of eight identical detector modules located on each corner of the *CGRO*. Each module contains a large-area detector (LAD) and a spectroscopy detector. In our analysis, we have used discriminator LAD (DISCLA) data with coarse-energy resolution (four channels covering $E > 25$ keV), spectroscopic time-tagged event (STTE) data, and spectroscopic high-energy resolution burst (SHERB) data with fine-energy binning (256 channels). A detailed description of BATSE instrumentation and data types can be found in Fishman et al. (1989).

BATSE was triggered by SGR 1900+14 bursts 63 times between 1998 May and 1999 January. For 22 of the brightest events, we obtained STTE or SHERB data with detailed spec-

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[7] Some examples of irregular temporal pattern of SGR 1900+14 bursts can be seen at http://gammaray.msfc.nasa.gov/batse/sgr/sgr1900/.

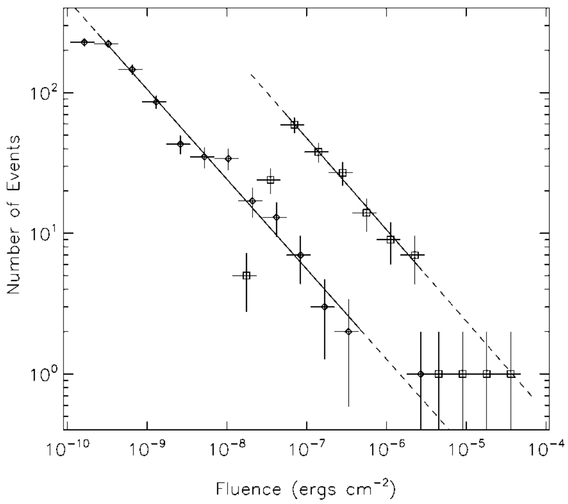

FIG. 1.—Differential distribution of the fluences of bursts from SGR 1900+14 as measured with *RXTE* (*diamonds*) and BATSE (*squares*). The solid lines denote the interval where used in the fit, and the dashed lines are the extrapolations of the model.

tral information. We fitted the background-subtracted source spectra to optically thin thermal bremsstrahlung (OTTB) and power-law models. The OTTB model, $F(E) \propto E^{-1} \times \exp(-E/kT)$, provides suitable fits ($0.83 < \chi^2_\nu < 1.32$) to all of the event spectra with temperatures ranging between 21.0 and 46.9 keV. The power-law model failed to fit most of the spectra. The mean of the OTTB temperatures for this sample of 22 events, appropriately weighted by uncertainties, is 25.7 ± 0.2 keV.

Woods et al. (1999a) performed an extensive search for untriggered BATSE events from SGR 1900+14. In addition to the 63 triggered events, they found 137 untriggered burst events between 1998 May 24 and 1999 February 3. In this study, we selected the 187 BATSE events (triggered and untriggered) that had DISCLA data. This data type is read out continuously (with the exception of data telemetry gaps) and therefore is available for the largest sample of events. We have excluded events that occurred in data gaps, events that were too weak to fit, and four events because of their distinction from typical SGR activity. The events on 1998 October 22 and 1999 January 10 with relatively hard spectra (Woods et al. 1999c) and the multi-episodic events on 1998 May 30 and September 1 (E. Göğüş et al. 1999, in preparation) will be discussed elsewhere. Given the long DISCLA data integration time (1.024 s) relative to typical burst durations (~0.1 s), we could only estimate the fluence for each event. In order to determine the fluence of each burst, we fitted the background-subtracted source spectrum to the OTTB model with a fixed kT of 25.7 keV, a reasonable choice considering the fairly narrow kT distribution of the triggered bursts. We find that the fluences of SGR 1900+14 bursts observed with BATSE range between 2×10^{-8} and 2.5×10^{-5} ergs cm^{-2}. For an estimated distance to SGR 1900+14 of 7 kpc (Vasisht et al. 1994), and assuming isotropic emission, the corresponding energy range is 1.1×10^{38}–1.5×10^{41} ergs.

3. PCA OBSERVATIONS

RXTE observed SGR 1900+14 for a total exposure time of ~180 ks between 1998 May and December. In this work, we have analyzed data from 32 pointed observations with the PCA. We performed an automated burst search similar to the one used on BATSE data described by Woods et al. (1999a). Using standard 1 data (2–60 keV) for all times where the source was above the Earth's horizon by more than 5°, we searched for bursts using the following methodology. For each 0.125 s bin, a background count rate was estimated by fitting a first-order polynomial to 5 s of data before and after each bin with a 3 s gap between the bin searched and the background intervals. Bins with count rates exceeding 1000 counts s^{-1} were assumed to contain burst emission and were excluded from background intervals. At the beginning (end) of each continuous stretch of data, extrapolations of background fits after (before) the bin were used to estimate the background count rate within the bin searched. A burst was defined as any continuous set of bins with count rates in excess of 5.5 σ above the estimated background. The count fluence of each burst was measured by simply integrating the background-subtracted counts over the bins covering the event.

In order to compare integrated counts obtained with the PCA and BATSE fluences, we determined a conversion factor between each PCA count and BATSE fluence. We assume a constant spectral model (OTTB with kT = 25.7 keV). First, we searched for simultaneous bursts observed with both instruments, and we found 13 events (six triggered events, three in the readout of triggered events, and four untriggered events in BATSE). We then computed the ratio of the BATSE fluence of each simultaneous event to the PCA counts, which ranges over a factor of ~2 between 4.65×10^{-12} and 1.15×10^{-11} ergs cm^{-2} counts^{-1}. The weighted mean of the ratios for SGR 1900+14 is 5.45×10^{-12} ergs cm^{-2} counts^{-1}, and the standard deviation $\sigma = 2 \times 10^{-12}$ ergs cm^{-2} counts^{-1}. Invoking this conversion factor, the fluence of the bursts from the PCA extends from 1.2×10^{-10} to 3.3×10^{-7} ergs cm^{-2} (in the BATSE energy range, $E > 25$ keV), and the burst energies range from 7×10^{35} to 2×10^{39} ergs.

4. STATISTICAL DATA ANALYSIS

4.1. *Fluence Distributions*

The fluences of BATSE bursts were binned in equally spaced logarithmic fluence steps ($dN/d \log E$; Fig. 1). Using a standard least-squares fitting method, we fitted a power-law model to data between 5.0×10^{-8} and 2.5×10^{-6} ergs cm^{-2}. Bursts at the low end of the distribution were excluded because of diminished detection efficiency, and those at the high end were excluded because of undersampling of the intrinsic distribution. The power-law exponent obtained is 0.65 ± 0.08 (the solid line passing through BATSE data in Fig. 1), which corresponds to $dN \propto E^{-1.65}\, dE$. We also employed a maximum likelihood analysis, instead of the least-squares method, in order to fit a power-law model to the unbinned fluence values within the same interval of fluences. This method yields $\gamma = 1.66^{+0.13}_{-0.12}$ for the energy exponent that agrees well with the least-squares fit.

Using the conversion factor that we derived from *RXTE* counts to BATSE fluence for SGR 1900+14, we determined the fluence of each RXTE burst (in the BATSE energy range) and distributed them over the same logarithmic fluence steps (Fig. 1). We first fitted binned *RXTE* fluences between 1.6×10^{-10} and 3.3×10^{-7} ergs cm^{-2} to a power-law model using a least-squares method that gives an exponent value of 0.64 ± 0.04 (the solid line passing through *RXTE* data in Fig. 1). The unbinned fluences were then fitted to the same model using the maximum likelihood method that obtained 1.66 ± 0.05 for the power-law exponent. Combined *RXTE* and BATSE fluences range from 1.2×10^{-10} to 2.5×10^{-5} ergs cm^{-2} (Fig. 1), which demonstrates that the power-law distri-

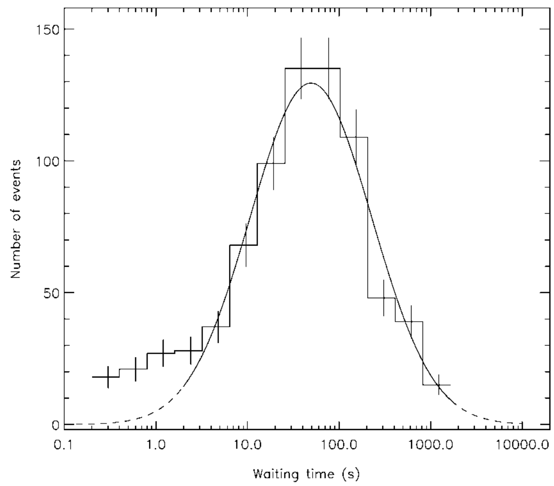

FIG. 2.—Distribution of the waiting times between successive *RXTE* PCA bursts from SGR 1900+14. The line shows the best-fit lognormal function. The solid portion of the line indicates the data used in the fit. The excess of short intervals above the model is due to the double-peaked events explained in the text.

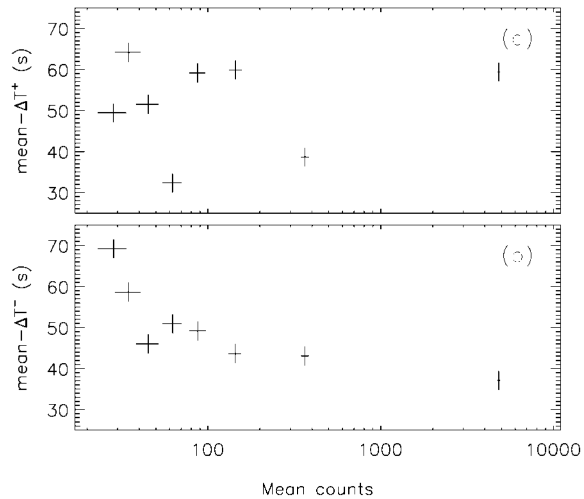

FIG. 3.—(*a*) Plot of mean waiting times until the next burst (ΔT^+) vs. mean counts that does not show any correlation ($\rho = 0.05$), and (*b*) plot of mean elapsed times since the previous burst (ΔT^-) vs. mean counts that shows a strong anticorrelation ($\rho = -0.93$).

bution of energies with an exponent $\gamma \approx 1.66$ is valid for SGR 1900+14 over 4 orders of magnitude.

4.2. *Waiting-Time Statistics*

We have measured the waiting times (ΔT) between successive bursts, uninterrupted by Earth occultation and data gaps, for 779 events. Figure 2 shows the distribution of waiting times that range from 0.25 to 1421 s. We fitted the (ΔT)-distribution to a lognormal function and found a peak at ∼49 s. The solid line in Figure 2 shows the interval used for the fit, and the dashed lines are the extrapolations of lognormal distribution. We do not include waiting times less than 2 s since these bursts appear to be double-peaked events in which the second burst peak appears shortly after the first one, although they are recorded as two distinct bursts. We were unable to generate a ΔT-distribution for BATSE bursts because of the much smaller number of events that occurred during a single orbital window.

In order to investigate any relations between waiting times until the next burst (ΔT^+) and the intensity of the bursts, we divided the sample of 779 events into eight intensity intervals, each of which contains approximately 100 events. We fitted the ΔT^+-distribution to a lognormal distribution and determined the mean ΔT^+ (i.e., where the fitted log normal distribution peaks) and the mean counts for each of the eight groups. We show in Figure 3*a* that there is no correlation between ΔT^+ and the energy of the bursts (Spearman rank-order correlation coefficient, $\rho = 0.05$, and the probability that this correlation occurs by a random data set, $P = 0.91$). We also searched for the relation between the elapsed times since the previous burst (ΔT^-) and the intensity of the bursts. Similar to the previous case, we subdivided the events into eight intensity intervals and determined the mean ΔT^- by fitting it to a lognormal distribution and the mean counts for each group individually. Figure 3*b* shows that there appears to be an anticorrelation between mean ΔT^- and the burst energy ($\rho = -0.93$, $P = 8 \times 10^{-4}$).

4.3. *Burst Durations*

Gutenberg & Richter (1956a, 1956b) demonstrated that there is a power-law relation between the magnitude or energy of the EQ events and the durations of the strong motion at short distances from an EQ region. In order to investigate whether a similar correlation exists for SGR events, we selected all 679 PCA bursts from the most active period of SGR 1900+14. In order to determine the durations of the bursts accurately, we used event-mode PCA data with a 1 ms time resolution. For 281 of the bursts selected, we obtained t_{90} durations (Koshut et al. 1996) of the bursts. Figure 4 shows that burst energies and durations are correlated ($\rho = 0.54$, $P \sim 10^{-24}$), although there is a significant spread of fluences at a given duration.

5. DISCUSSION

The power-law size distribution of SGR 1900+14 bursts with an index $\gamma = 1.66$ is similar to those found for SGR 1806−20 (Cheng et al. 1996) and SGR 1627−41 (Woods et al. 1999b). The lack of a high-energy cutoff in the differential size distribution indicates that the highest energy events are not well sampled in our distribution.

The distribution of waiting times between successive SGR

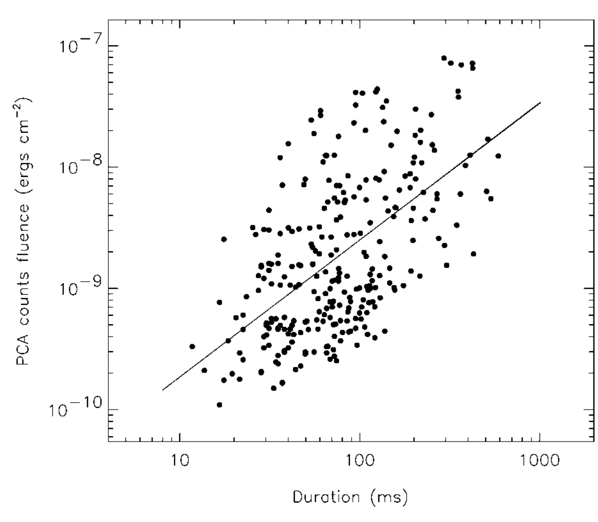

FIG. 4.—Scatter plot of the PCA fluence vs. duration for 281 SGR 1900+14 bursts that shows a correlation between them ($\rho = 0.54$). The solid line is a power law with an exponent 1.13 obtained via least-squares fitting.

1900+14 bursts is characterized by a lognormal function similar to that of SGR 1806−20 (Hurley et al. 1994). Waiting times between SGR 1900+14 bursts are on average shorter than those of SGR 1806−20 since all SGR 1900+14 bursts occurred during the most active period of the source. There is no correlation between the intensity of the burst and the waiting time until the following burst. This result agrees well with the results of Laros et al. (1987) for SGR 1806−20 and distinguishes the physical mechanism of SGR 1900+14 bursts from that of type II X-ray bursts from the Rapid Burster (Lewin et al. 1976) in which the burst energy is proportional to the waiting time until the next burst. We find an anticorrelation between the intensity of the bursts and the waiting time since the previous bursts. This is very different from type I X-ray bursts (thermonuclear flashes; see Lewin, van Paradijs, & Taam 1993) for which there is a rough positive correlation.

There is evidence of a positive correlation between the energy and the duration of SGR 1900+14 bursts. Similar behavior was also observed for EQs (Gutenberg & Richter 1956a, 1956b) and solar flares (Lu et al. 1993).

The EQ size distribution appears to be a power law with an exponent between 1.4 and 1.8 independent of geographic location (Gutenberg & Richter 1956a, 1965, p. 16; Lay & Wallace 1995). Using data taken from the *Solar Maximum Mission* (*SMM*), Crosby, Aschwanden, & Dennis (1993) found a power-law size distribution for 12,000 solar flares with exponents ranging between 1.53 and 1.73. The *SMM* results have been confirmed by the results from the *International Cometary Explorer* for 4350 flares in which an exponent of 1.6 was found (Lu et al. 1993). Gershberg & Shakhovskaya (1983) found that the size distribution of stellar flares from 23 stars display a power law with an exponent between 1.5 and 2.1.

Chen, Bak, & Obukhov (1991) argued that EQ dynamics is described by a self-organized critical system. Crosby et al. (1993) similarly suggested that the size distribution of solar flares reflects an underlying system in a state of self-organized criticality (see Bak, Tang, & Wiesenfeld 1988) where many composite systems will self-organize to a critical state in which a small perturbation can trigger a chain reaction that affects any number of elements within the system.

We have been unable to find clear results in the literature on the distribution of waiting times between successive solar flares or EQs. Wheatland, Sturrock, & McTiernan (1998) predicted that the distribution of waiting times of solar flares displays a power law, while Biesecker (1994) proposed that it is consistent with a time-dependent Poisson process. Nishenko & Buland (1987) showed that a waiting-time distribution of large EQs is well described by a lognormal function. In recent work by Nadeau & McEvilly (1999), there is evidence of a lognormal distribution of waiting times between micro-EQs.

The large number of bursts in our samples allows us to test stringently the power-law size distribution proposed by Cheng et al. (1996); we find that the size distribution of SGR 1900+14 bursts follows a power law of index 1.66 over more than 4 orders of magnitude in burst fluence. This behavior, along with a lognormal waiting-time distribution and energy-correlated burst durations, is characteristic of self-organized critical systems, in general, and earthquakes and solar flares, in particular. In the magnetar model, the triggering mechanism for SGR bursts is a hybrid of starquakes and magnetically powered flares (Thompson & Duncan 1995). When magnetic stresses induce elastic strains in the crust, the stored potential energy is predominantly magnetic rather than elastic. In contrast to an EQ, this allows much of the energy to be released directly into a propagating disturbance of the external magnetic field[8] of the neutron star, and in contrast to a solar flare, it is the rigidity of the crust that provides a gate or trigger for the energy release. The extended power-law distribution of burst fluences suggests that the average radiative efficiency does not vary significantly over 4 orders of magnitude in burst energy, and it provides a strong constraint on burst-emission models (C. Thompson et al. 1999, in preparation).

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[8] Small-scale fractures occurring deep in the crust excite internal seismic waves that couple only indirectly to external Alfvén modes.

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