THE ASTROPHYSICAL JOURNAL, 431:L31–L34, 1994 August 10

NETWORK SYNTHESIS LOCALIZATION OF TWO SOFT GAMMA REPEATERS

KEVIN HURLEY
University of California, Space Sciences Laboratory, Berkeley, CA 94720-7450; khurley@sunspot.ssl.berkeley.edu

M. SOMMER
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, D-85740 Garching, Germany

C. KOUVELIOTOU, G. FISHMAN, AND C. MEEGAN
NASA–Marshall Space Flight Center, ES 62, Huntsville, AL 35812

T. CLINE
NASA–Goddard Space Flight Center, Code 661, Greenbelt, MD 20771

AND

M. BOER AND M. NIEL
Centre d'Etude Spatiale des Rayonnements, B.P. 4346, 31400 Toulouse Cedex, France

Received 1994 February 23; accepted 1994 May 23

ABSTRACT

We introduce the method of "network synthesis," which allows the detection of very weak gamma-ray transient signals in the data of the *Ulysses* gamma-ray burst (GRB) experiment from repeating sources. It consists of defining a grid of α, δ values, and for each BATSE detection of a burst from a soft gamma repeater, predicting the arrival time of the burst at *Ulysses* and co-adding the *Ulysses* data rephased so that the burst signals are aligned in time and produce a detectable pulse. We demonstrate that this method identifies the position of the soft repeater SGR 1806−20, and apply it to the repeater B1900+14. We show that the counterpart to this burst source is probably in or in the vicinity of the Galactic supernova remnant G42.8+0.6.

Subject headings: gamma rays: bursts — stars: neutron

1. INTRODUCTION

The "classical" gamma-ray bursts are distinguished by their hard energy spectra, isotropic spatial distribution, durations as long as hundreds of seconds, and the fact that no source has yet definitely been observed to repeat. Their origin remains a mystery. However, three sources with special characteristics, known as soft gamma repeaters (SGRs), have been discovered using gamma-ray burst (GRB) experiments. They have soft energy spectra and short durations and have definitely been observed to repeat. The SGRs appear to be quite rare and related to neutron stars with rather special properties (Norris et al. 1991; Hurley et al. 1994). One is SGR 0525−66, which produced the anomalously intense 1979 March 5 burst (Cline et al. 1980) and has a location consistent with the N49 supernova remnant (SNR) in the Large Magellanic Cloud (LMC) (Cline et al. 1982); it has been observed to repeat 15 times after the initial event (Golenetskii et al. 1984). The second is SGR 1806−20, which has burst over 100 times (Atteia et al. 1987; Laros et al. 1987; Kouveliotou et al. 1994) and whose source is in the Galactic supernova remnant G10.0−0.3 (Kulkarni & Frail 1993; Kulkarni et al. 1994; Murakami et al. 1994). The third is SGR 1990+14 (=B1900+14), which burst 3 times in 1979 (Mazets et al. 1979) and 3 times in 1992 (Kouveliotou et al. 1993). Until now, this object, which is located very near the Galactic plane, had no obvious counterpart.

The classical gamma-ray bursters may be localized to arcminute accuracy by the triangulation method: the arrival times are compared at a network of three or more detectors to produce intersecting annuli, which form an error box. In the special case of soft gamma repeaters, a network of only two detectors can be used to derive an error box (as opposed to an annulus) if both instruments observe a number of bursts and the direction of the interspacecraft vector changes sufficiently between observations, simulating the effect of a multispacecraft network. Here we demonstrate that it is possible to utilize this method *even if one of the detectors does not observe any of the individual repeating bursts above its threshold but does detect the sum of them.* In analogy with aperture synthesis in radio astronomy, we call this method "network synthesis." In this *Letter* we demonstrate that the third interplanetary network, primarily consisting, after late 1992, of the the BATSE and *Ulysses* GRB experiments, localized the soft gamma repeater SGR 1806−20 by network synthesis to a position consistent with that of the supernova remnant G10.0−0.3, and has derived a locus of possible positions for the soft repeater SGR 1900+14 which reduce the area of its previous error box by a factor of ~70 and suggest that its counterpart is in or in the vicinity of the Galactic supernova remnant G42.8+0.6.

2. INSTRUMENTATION

The BATSE and *Ulysses* GRB experiments are described in Fishman et al. (1989) and Hurley et al. (1992), respectively. Briefly, a BATSE large-area detector consists of a flat scintillator with surface area 2025 cm^2 covering the 30–1900 keV energy range, while the *Ulysses* GRB sensor consists of two hemispherical scintillators with projected area 20 cm^2 in any direction, covering the 25–150 keV energy range. The *Ulysses* instrument operates in both triggered and real-time modes, but only the latter is applicable here. Depending upon the spacecraft telemetry rate, 25–150 keV count rates are transmitted with 0.25, 0.5, 1, or 2 s resolution in this mode.

3. OBSERVATIONS

BATSE detected six bursts from SGR 1806−20 between 1993 September 29 and November 10, but they were too weak

TABLE 1

CHARACTERISTICS OF SIX BURSTS FROM SGR 1806−20

BATSE Trigger Time[a] T_0 (1993)	Net BATSE Counts C_B	Duration t_B (s)	*Ulysses* Time Resolution Δt (s)	Expected *Ulysses* Counts C_U
Sep 29 (34801)	750	0.1	1	13
Sep 29 (73581)	2100	0.1	0.25	38
Sep 29 (83733)	638	0.025	0.5	11
Oct 5 (84169)	1700	0.05	0.5	31
Oct 9 (82260)	1750	0.03	0.5	31
Nov 10 (38943)	1000	0.03	0.5	18

[a] Numbers in parentheses are seconds.

to trigger the *Ulysses* GRB detector. The real-time data were searched in the *Ulysses* crossing-time windows defined by the BATSE localizations and the positions of the *Ulysses* spacecraft; such searches are routinely carried out on all BATSE bursts and frequently result in the detection of events just below the trigger threshold, but in no case here did these searches reveal statistically significant count rate increases which would have been the signatures of untriggered bursts. Table 1 summarizes the characteristics of the BATSE bursts, and gives the *Ulysses* GRB time resolution and expected counts from these events. The expected number of counts for *Ulysses* is $\sim 0.018 \pm 0.01$ times the number of BATSE counts, based on a comparison of ~ 80 BATSE and *Ulysses* classical (hard spectrum) cosmic bursts.

4. THE NETWORK SYNTHESIS METHOD

With a background count rate of ~ 480 counts s^{-1}, it is evident from Table 1 why *Ulysses* did not trigger on any of the BATSE bursts. Individually, the contribution of a burst to the count rate in *Ulysses*' 0.125 s long trigger window would have been at most about 38 counts compared to a 60 count background rate, less than the 6–7 σ trigger criterion normally in use. But the sum of the predicted counts would be ~ 142 counts, which can be a significant increase over the background rate in a 1 s long real-time data interval. Motivated by this fact, we constructed a rectangular grid of right ascension and declination values covering the second interplanetary network error box for SGR 1806−20 [the initial error box of Atteia et al. 1987 was later revised to an ellipse centered at $\alpha(2000) = 272^\circ\!.1499$, $\delta(2000) = -20^\circ 7310$, with major-axis length $1^\circ\!.42$ approximately aligned with right ascension and minor-axis length $0^\circ\!.06$ approximately aligned with declination]. For each point in the grid, and each burst, we computed the arrival time at *Ulysses* to an accuracy of better than ± 10 ms and extracted a portion of the real-time data, so that a total of six stretches of data was obtained with time resolution of 0.25, 0.5, or 1 s. These data stretches were then individually rebinned to a common time resolution and co-added in phase in such a way that their sum, a single time series, contained the predicted burst arrival time in a single time bin. (Note that the burst duration t_B and the *Ulysses* time resolution Δt ensure that these events practically never straddle two time bins.) The optimum grid spacing is such that the difference in arrival times at the spacecraft between adjacent grid points is equal to the minimum time resolution of the data stretches to be co-added. (The spacing is also a function of the angle between the burst arrival direction and the interspacecraft vector, and the interspacecraft distance; the latter varied between ~ 2200 and 2500 light-seconds for the six bursts from SGR 1806−20, and ~ 2900 and 3100 for the three bursts from SGR 1900+14.) Finer spacing oversamples, producing identical time series, while coarser spacing undersamples and could result in the source position being missed. In this case, for example, for 0.5 s resolution, the optimum spacing is $\sim 0^\circ\!.008$ in α and $\sim 0^\circ\!.0125$ in δ.

Due to the variable time resolution and nonlinear compression of the *Ulysses* data, a choice must be made of the bursts to include in this procedure. If the first BATSE event is included, the common time resolution will be 1 s, the background rate in the co-added time series will be approximately 2880 counts, and a 142 count excess will appear at about the 2.6 σ level. The uncertainty due to data compression will be ~ 130 counts (the relative error increases with rebinning). However, if this event is excluded, the common time resolution becomes 0.5 s, and an excess of ~ 129 counts should appear over a background of ~ 1200 counts, or 3.7 σ. The uncertainty due to data compression will be ~ 60 counts. Thus the network synthesis procedure consists of constructing a co-added time series for each point in the grid and testing the single bin in each series where the sum of the bursts would appear if the source were at the grid point, for a significant excess over background. Note, however, that to be accepted an excess must satisfy several criteria in addition to statistical significance. First, it must have an intensity in the correct range, that is, the *Ulysses* fluence in counts must be $\sim 0.018 \pm 0.01$ times the BATSE fluence. Second, and more important, the excesses must correspond to a well-determined region of the grid. To understand this, imagine a network of *simultaneously* operating detectors, each at the actual position of the *Ulysses* spacecraft at the time of one of the bursts. If this "virtual network" observed a single, hypothetical burst from a position in the grid, it would localize it to an error box whose size and shape were determined by the spacecraft positions and timing uncertainties. The excesses found in the network synthesis method must therefore correspond to points on the grid which conform to the virtual network error box. The entire procedure has been verified by a complete Monte Carlo simulation and, as we now demonstrate, by actual application to the data from SGR 1806−20.

5. NETWORK SYNTHESIS LOCALIZATION OF SGR 1806−20

The grid constructed about the revised Atteia et al. (1987) error ellipse displayed excesses at just one locus of points, and it was consistent with the virtual network error box. These points are displayed in Figure 1, which also shows the error ellipse, the virtual network error box, and the position of the supernova remnant G10.0−0.3 (Kulkarni & Frail 1993), which has now been demonstrated to correspond to SGR 1806−20 (Kouveliotou et al. 1994; Murakami et al. 1994). The excess count rates in the *Ulysses* data were 4.3 ± 1.6 σ above background, where the uncertainty arises from the data compression. One hundred sixty-one excess counts were detected, leading to a ratio of 0.024 between the *Ulysses* and BATSE fluences, well within the acceptable range. From Figure 1 it is clear that network synthesis has correctly identified the position of SGR 1806−20. However, two additional checks were performed. First, the method was carried out on the full data set of six bursts; the same locus of points was identified, albeit with lower significance (3.3 σ). The other check was carried out with five bursts on a control region whose shape was identical to the one about the error ellipse. It was centered at $\alpha(2000) =$

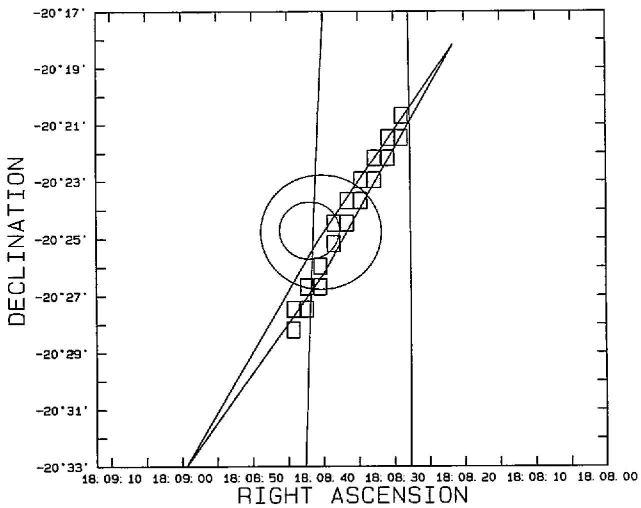

FIG. 1.—Map of the region around SGR 1806−20 (J2000 coordinates). The vertical lines are the sides of the second interplanetary network error ellipse. The rectangles represent the regions on the grid where excess count rates were identified; the grid is completely sampled in α but slightly undersampled in δ. The diamond shows a typical virtual network error box centered at $\alpha = 272^\circ.168$, $\delta = -20^\circ.428$. The large circle is at the approximate outer radio contours of G10.0−0.3, and the small circle gives the ASCA error box for SGR 1806−20.

$272^\circ.168$, $\delta(2000) = -21^\circ.1$, and should have contained at most about one randomly occurring excess (none was found). We finally note that a 4.3 σ excess corresponds to a probability of chance occurrence of 8.5×10^{-6}, but that approximately 25 independent virtual network error boxes are contained within the error ellipse; reduction of the chance probability by the number of trials leads to a probability of $\sim 2 \times 10^{-4}$. Having demonstrated that network synthesis works both in theory and in practice, we turn to the case of the soft repeater SGR 1900+14.

6. NETWORK SYNTHESIS LOCALIZATION OF SGR 1900+14

SGR 1900+14 was discovered by Mazets et al. (1979), and three subsequent bursts were detected by BATSE in 1992 (Kouveliotou et al. 1993). Table 2 summarizes the characteristics of the three BATSE events and the *Ulysses* GRB detector configuration. As for SGR 1806−20, the individual bursts were too weak to trigger the *Ulysses* GRB experiment, but their sum should give a detectable signal ($\sim$86 counts) in a 0.5 s real-time data interval. To find the signal from SGR 1900+14, we searched an area which consisted of those points both (1) within the annulus centered at $\alpha(2000) = 223^\circ.678$, $\delta(2000) = -3^\circ.356$, radii $63^\circ.9$ and $64^\circ.2$ (i.e., considerably wider than the revised KONUS error box) and (2) contained within

TABLE 2

CHARACTERISTICS OF THREE BURSTS FROM SGR 1900+14

BATSE Trigger Time[a] T_0 (1992)	Net BATSE Counts C_B	Duration t_B (s)	*Ulysses* Time Resolution Δt (s)	Expected *Ulysses* Counts C_U
June 19 (64666)	1900	0.5	0.5	34
July 8 (18957)	1400	0.16	0.5	25
Aug 19 (17859)	1500	0.04	0.25	27

[a] Numbers in parentheses are seconds.

the BATSE error circle (Kouveliotou et al. 1993). The grid spacing was $0^\circ.008$ in α and $0^\circ.025$ in δ, and the total area searched was 2.5 square degrees. Within this area, a total of 10 regions were identified which corresponded to excesses above 3 σ. The most likely source region is an area around $\alpha(2000) = 286^\circ.828$, $\delta(2000) = 9^\circ.450$, corresponding to a 3.91 ± 1.2 σ excess (again, the uncertainty arises from the data compression). The number of counts above background was 113, or a *Ulysses*/BATSE ratio of 0.023. A 3.91 σ excess corresponds to a chance probability of 4.6×10^{-5}; reduction by the number of trials ($\sim$138 virtual error boxes are contained within the search region) results in a chance probability of 6×10^{-3}. Among the nine other regions, the next most likely is around $\alpha(2000) = 285^\circ.956$, $\delta(2000) = 13^\circ.100$ (3.87 σ). The difference in significance between this and the region above is negligible. The eight remaining regions corresponds to values less than 3.4 σ (adjusted probabilities greater than 0.05). Neither of the two most probable regions lies exactly within the revised KONUS 1 σ error box (E. Mazets 1993, private communication) but the first one grazes it and overlaps the 3 σ error box, while the second lies well outside. For this reason, and the one we discuss below, we consider the former to be the prime candidate for the counterpart to SGR 1900+14.

7. DISCUSSION

Figure 2 shows the network synthesis localization of SGR 1900, the virtual network error box, and a portion of the KONUS error box. We have compared the 10 network synthesis positions with catalogs of radio supernova remnants (Green 1991; Reich, Reich, & Fürst 1990), and the two most probable positions with cataloged objects in SIMBAD. An SGR/SNR connection is strongly indicated by the N49/1979 March 5 association (Cline et al. 1980) and the SGR 1806−20/G10.0−0.3 association (Kouveliotou et al. 1994; Murakami et al. 1994; Kulkarni et al. 1994). The shell-like radio supernova remnant G42.8+0.6 (Green 1991), suggested as a possible counterpart by Kouveliotou et al. (1994), is the only one which

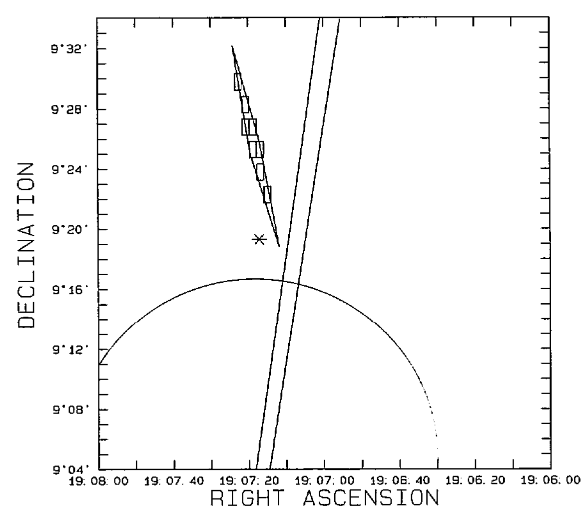

FIG. 2.—Map of the region around SGR 1900+14 (J2000 coordinates). The pair of approximately vertical lines gives the boundary of the revised 1 σ KONUS error box. The rectangles represent the regions on the grid where excess count rates were identified; the grid is completely sampled in α but slightly undersampled in δ. The diamond shows a typical virtual network error box centered at $\alpha = 286^\circ.828$, $\delta = 9^\circ.425$. The circle is at the approximate outer radio contours of G42.8+0.6. The asterisk is at the position of the *ROSAT* source RX J190717+0919.3 (Vasisht et al. 1994).

lies close to a position. A very rough idea of its distance may be obtained by applying the surface brightness–diameter relation to it (Huang & Thaddeus 1985); we obtain a distance of about 7 kpc, with an uncertainty of a factor of ~ 2. At this distance, the peak intrinsic luminosities of the bursts observed by Mazets et al. (1979) would be $\sim 8 \times 10^{40}$ ergs s^{-1}, and for the BATSE events it would be 10^{40} ergs s^{-1}. In both cases, therefore, they would be quite super-Eddington. Further details about G42.8+0.6 appear in a companion *Letter* (Vasisht et al. 1994).

As Figure 2 indicates, the virtual network error box just grazes the outer radio contours of the remnant. This could be an indication that the neutron star counterpart to SGR 1900+14 has a velocity comparable to that of the SNR shell (see, e.g., Frail & Kulkarni 1991 or Cordes, Romani, & Lundgren 1993) and is indeed far from the center of the SNR, as appears to be the case with N49 and G10.0−0.3. However, it is also possible that the real counterpart to SGR 1900+14 has not yet been identified in the radio surveys. Vasisht et al. (1994) give the positions of seven *ROSAT* X-ray sources; none corresponds to the position of a statistically significant excess with a virtual network error box. However, the proximity of RXJ 190717+0919.3 both to the outer radio contours of G42.8+0.6 and to the error box of Figure 2 suggests that this is a prime candidate for the counterpart. Further X-ray and radio observations of this object are now being planned and should eventually establish the true counterpart.

Finally, we note that, with some modifications, the network synthesis method can be applied to search for classical repeating gamma-ray burst sources (e.g., Wang & Lingenfelter 1993). This application of the method is currently being developed and will be reported on elsewhere.

The *Ulysses* GRB experiment was constructed at the CESR in France with support from the Centre National d'Etudes Spatiales and at the Max-Planck-Institut in Germany with support from FRG contracts 01 ON 088 ZA/WRK 275/4-7.12 and 01 ON 88014. K. H. gratefully acknowledges assistance from JPL contract 958056 and NASA grant NAG 5-1559, and helpful discussions with D. Hartmann, S. Kulkarni, and B. Schaefer. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Atteia, J.-L., et al. 1987, ApJ, 320, L105
Cline, T., et al. 1980, ApJ, 237, L1
———. 1982, ApJ, 255, L45
Cordes, J., Romani, R., & Lundgren, S. 1993, Nature, 362, 133
Fishman, G., et al. 1989, in Proc. *GRO* Science Workshop, ed. W. N. Johnson (Greenbelt: NASA), 39
Frail, D., & Kulkarni, S. 1991, Nature, 352, 785
Golenetskii, S., et al. 1984, Nature, 307, 41
Green, D. 1991, PASP, 103, 209
Huang, Y.-L., & Thaddeus, P. 1985, ApJ, 295, L13
Hurley, K., et al. 1992, A&AS, 92, 401
———. 1994, ApJ, 423, 709
Kouveliotou, C., et al. 1993, Nature, 362, 728
———. 1994, Nature, 368, 125
Kulkarni, S., & Frail, D. 1993, Nature, 365, 33
Kulkarni, S., et al. 1994, Nature, 368, 129
Laros, J., et al. 1987, ApJ, 320, L111
Mazets, E., et al. 1979, Soviet Astron. Lett., 5 (No. 6), 343
Murakami, T., et al. 1994, Nature, 368, 127
Norris, J., Hertz, P., Wood, K., & Kouveliotou, C. 1991, ApJ, 366, 240
Reich, W., Reich, P., & Fürst, E. 1990, A&AS, 83, 539
Vasisht, G., Kulkarni, S. R., Frail, D. A., & Greiner, J. 1994, ApJ, 431, L35
Wang, V., & Lingenfelter, R. 1993, ApJ, 416, L13