THE ASTROPHYSICAL JOURNAL, 534:L23–L25, 2000 May 1
© 2000. The American Astronomical Society. All rights reserved. Printed in U.S.A.

INTERPLANETARY NETWORK LOCALIZATION OF GRB 991208 AND THE DISCOVERY OF ITS AFTERGLOW

K. HURLEY,[1] T. CLINE,[2] E. MAZETS,[3] R. APTEKAR,[3] S. GOLENETSKII,[3] D. FREDERIKS,[3] D. FRAIL,[4]
S. KULKARNI,[5] J. TROMBKA,[2] T. MCCLANAHAN,[2] R. STARR,[6] AND J. GOLDSTEN[7]
Received 2000 February 4; accepted 2000 March 15; published 2000 April 25

ABSTRACT

The extremely energetic ($\sim 10^{-4}$ ergs cm^{-2}) gamma-ray burst (GRB) of 1999 December 8 was triangulated to an ~14 arcmin^2 error box ~1.8 days after its arrival at Earth with the third interplanetary network (IPN), which consists of the *Ulysses*, *Near-Earth Asteroid Rendezvous*, and *Wind* spacecraft. Radio observations with the Very Large Array ~2.7 days after the burst revealed a bright fading counterpart whose position is consistent with that of an optical transient source with a redshift of 0.707. We present the time history, peak flux, fluence, and refined 1.3 arcmin^2 error box of this event and discuss its energetics. This is the first time that a counterpart has been found for a GRB localized only by the IPN.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Many gamma-ray burst counterparts have now been identified using the rapid, precise localizations available from the *BeppoSAX* spacecraft, as well as from the *Rossi X-Ray Timing Explorer*, starting with GRB 970228 (Costa et al. 1997; van Paradijs et al. 1997). Such detections occur at a low rate (~8 yr^{-1}), and they have been limited to the long-duration events so far, but they have confirmed the cosmological origin of at least this class of bursts. Since 1977, interplanetary networks of omnidirectional gamma-ray burst (GRB) detectors have provided precise triangulations of both short and long bursts at rates up to ~1 week^{-1}, but often the networks have been incomplete or the data return from the interplanetary spacecraft has been slow. The present, third interplanetary network (IPN) is now complete with *Ulysses* and *Near-Earth Asteroid Rendezvous* (*NEAR*) as its distant points (Cline et al. 1999) and, in conjunction with numerous near-Earth spacecraft, can produce precise GRB error boxes within ~1 day, making them useful for multiwavelength follow-up observations. Here we present the observations of GRB 991208, which was rapidly localized to a small error box, leading to the identification of its radio and optical afterglow and eventually to the measurement of its redshift.

2. IPN OBSERVATIONS

GRB 991208 was observed by the *Ulysses* GRB (Hurley et al. 1992), KONUS-*Wind* (Aptekar et al. 1995), and *NEAR* X-Ray/Gamma-Ray Spectrometer (XGRS; Goldsten et al. 1997) experiments. *Ulysses* (in heliocentric orbit), *NEAR* (approaching rendezvous with the asteroid Eros), and *Wind* were 2176, 937, and 1.5 lt-s from Earth, respectively.

We focus here on the *Ulysses* and *NEAR* data; KONUS data will be presented elsewhere. The *Ulysses* and XGRS light curves are shown in Figure 1. Although *Ulysses* recorded the first 57 s of the burst with 0.03125 s resolution in the triggered mode, the peak of the event occurred slightly later, and we have shown the 0.5 s resolution real-time data in the figure. The XGRS BGO anticoincidence shield is employed as the *NEAR* burst monitor, and the only time history data available from it are 1 s resolution count rates for the 100–1000 keV energy range. The burst can be characterized by a T_{90} duration of 68 s, placing it firmly in the "long" class of bursts (Hurley 1992; Kouveliotou et al. 1993). The event-integrated *Ulysses* spectrum is well fit between 25 and 150 keV by a power law, thermal bremsstrahlung, or blackbody spectrum. For the following analysis, we adopt the power law, which has a photon index 1.68 ± 0.19 and a χ^2 of 4.3 for 11 degrees of freedom (Fig. 2). The 25–100 keV fluence is 4.9×10^{-5} ergs cm^{-2}, with an uncertainty of $\sim \pm 10\%$ due to count-rate statistics and systematics. Since the XGRS shield provides only very low resolution (40 minutes) spectral data, we can only estimate the fluence in the XGRS energy range from its light curve to be about the equivalent of that observed by *Ulysses*. Thus, the total fluence above 25 keV is $\sim 10^{-4}$ ergs cm^{-2}. Bursts with this intensity or greater occur at a rate $\lesssim 10$ yr^{-1}. Since the peak of the event occurs when only the 0.5 s *Ulysses* data are available, we can estimate the peak flux only over this time interval; it is $\sim 5.1 \times 10^{-6}$ ergs cm^{-2} s^{-1}, 25–100 keV ($\sim \pm 10\%$), with a contribution in the 100–1000 keV energy range which is again probably equivalent.

A preliminary ~14 arcmin^2 IPN error box was circulated ~44 hr after the Earth-crossing time of the event (04:36:53 UT; Hurley et al. 1999). The final error box is shown in Figure 3 and nests within the preliminary one; it has an area of ~1.3 arcmin^2. Its coordinates are given in Table 1. Also shown in Figure 3 is the position of the radio counterpart to the burst detected by Frail (1999). We note that this is the first time that a GRB position determined by the third IPN alone (i.e., no *Compton Gamma-Ray Observatory* [*CGRO*] BATSE or *BeppoSAX* observations) has been successfully used for multiwavelength counterpart searches.

3. OBSERVATIONS WITH NRAO VERY LARGE ARRAY

Very Large Array (VLA)[8] observations were begun on 1999 December 10.92 UT, 2.73 days after the gamma-ray burst. In order to image the entire 14 arcmin^2 initial IPN error box (Hur-

[1] University of California, Berkeley, Space Sciences Laboratory, Berkeley, CA 94720-7450; khurley@sunspot.ssl.berkeley.edu.
[2] NASA Goddard Space Flight Center, Greenbelt, MD 20771.
[3] Ioffe Physico-Technical Institute, St. Petersburg, 194021 Russia.
[4] National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.
[5] Palomar Observatory, 105-24, Caltech, Pasadena, CA 91125.
[6] Department of Physics, Catholic University of America, Washington, DC 20064.
[7] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723.

[8] The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

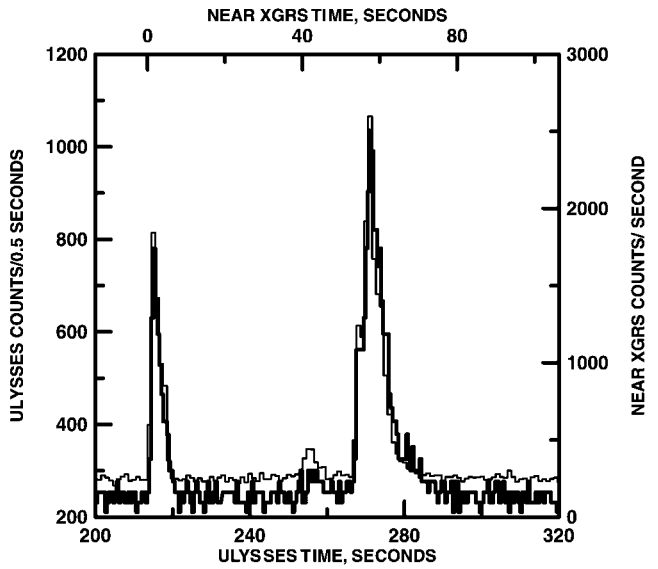

FIG. 1.—Time histories of GRB 991208 as observed by *Ulysses* GRB (22–150 keV, *thick line*) and *NEAR* XGRS (100–1000 keV, *thin line*). The *Ulysses* data are compressed on board the spacecraft and decompressed on the ground, leading to discrete count-rate levels.

ley et al. 1999) with the VLA at 8.46 GHz, two pointings were required, each with a field of view at half-power response of 5′.3. The full 100 MHz bandwidth was used in two adjacent 50 MHz bands centered at 8.46 GHz. A single pointing was also made at 4.86 GHz, but the bandwidth was halved in order to image the full 9′ field of view without distortion. The flux density scale was tied to the extragalactic source 3C 48 (J0137+331), while the array phase was monitored by switching between the GRB and the phase calibrators J1637+462 (at 8.46 GHz) and J1658+476 (at 4.86 GHz).

There were three radio sources inside the initial IPN error box (Fig. 3). Of these, two were previously known from an earlier survey of this part of the sky (Becker, White, & Helfand 1995). The third source, located at (epoch J2000) $\alpha = 16^{h}33^{m}53^{s}.50$ ($\pm 0^{s}.01$), $\delta = +46°27'20''.9$ ($\pm 0''.1$), was near the center of the initial IPN error box. On the basis of its position, compactness (<0″.8), and a rising flux density between 4.86 and 8.46 GHz (327 ± 45 and 707 ± 39 μJ, respectively), Frail (1999) proposed that it was the afterglow of GRB 991208. Despite the proximity of this location to the Sun (~70°), numerous optical observations were carried out, and this suggestion was quickly confirmed by the independent detection of a coincident optical source, not visible on the Digital Sky Survey (Castro-Tirado et al. 1999).

In the week following the afterglow discovery, it was determined that the optical flux faded as a power law with a rather steep temporal decay index $\alpha \simeq -2.15$ (where $F_\nu \propto t^\alpha$; Jensen et al. 1999; Garnavich & Noriega-Crespo 1999; Masetti et al. 1999). Optical spectroscopy emission lines from a presumed host galaxy, if identified with [O II] and [O III] features, place

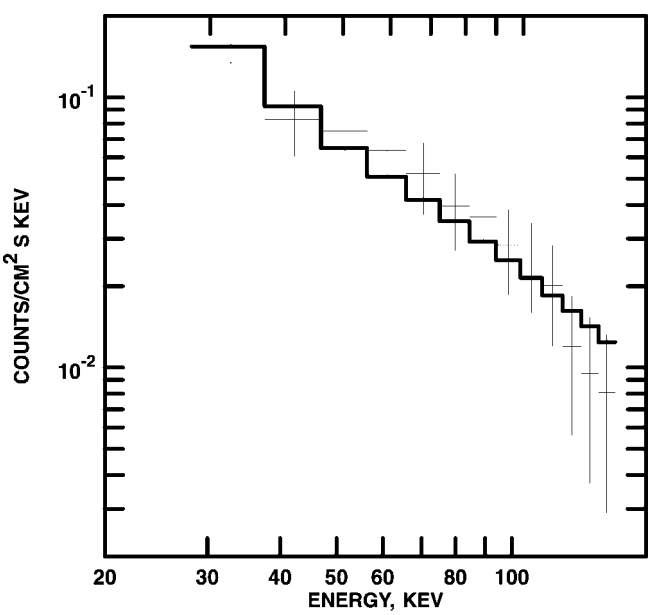

FIG. 2.—Energy spectrum of GRB 991208 as observed by *Ulysses* GRB (*crosses*) and the fitted power-law spectrum (*line*).

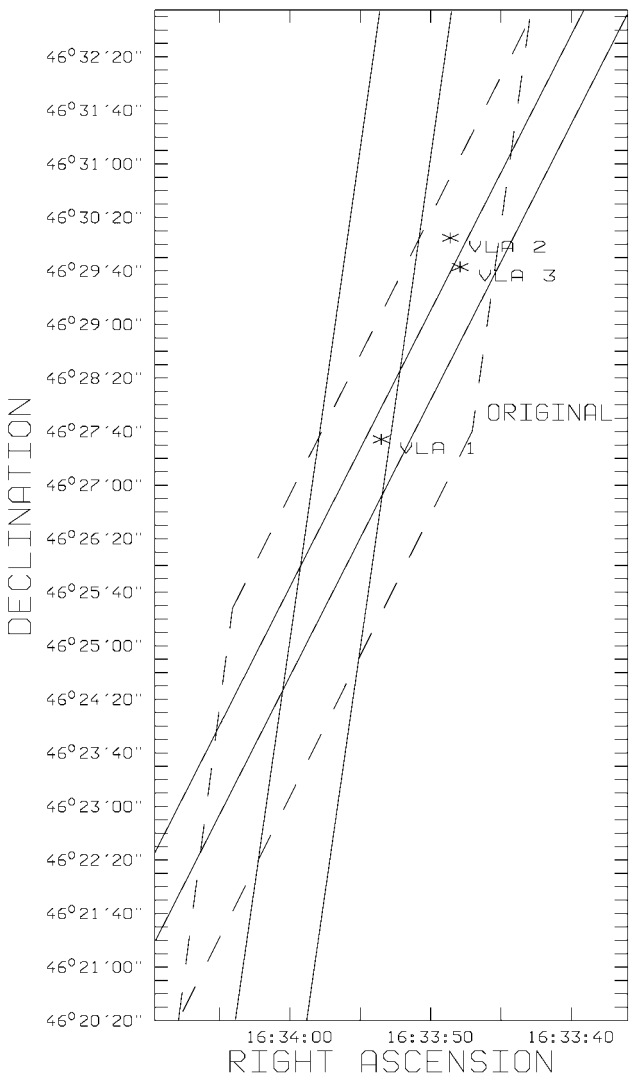

FIG. 3.—Original and final IPN error boxes for GRB 991208 (3 σ confidence). The original error box (Hurley et al. 1999) is drawn with dashed lines. The final error box is defined by the intersection of the 30″ *Ulysses*-KONUS annulus and the 52″ *Ulysses-NEAR* annulus and has an area of 1.3 arcmin^2. Three sources are indicated. Two field sources in the upper right-hand corner are marked VLA 2 and VLA 3; their flux densities are 3.4 and 0.4 mJy, respectively. VLA 1 is the counterpart. It lies at roughly at the 96% confidence contour.

TABLE 1
IPN Error Box for GRB 991208
(3 σ confidence)

Location	α(2000) (deg)	δ(2000) (deg)
Center	248.4848	46.4413
Corners	248.4727	46.4487
	248.5021	46.4078
	248.4674	46.4747
	248.4969	46.4338

GRB 991208 at a redshift $z = 0.707 \pm 0.002$ (Dodonov et al 1999), making this the third closest GRB with a spectroscopically measured redshift. GRB 991208 has been no less interesting at radio wavelengths. It has the brightest radio afterglow detected to date, and consequently it has been detected and is well studied between 1 and 350 GHz (Pooley 1999; Shepherd et al. 1999; Bremer et al. 1999).

4. DISCUSSION

For a 25–1000 keV fluence of 10^{-4} ergs cm^{-2} and a redshift $z = 0.707$, the isotropic energy of this burst would have been 1.3×10^{53} ergs; for a peak flux of $\sim 10^{-5}$ ergs cm^{-2} s^{-1} in the same energy range, the isotropic peak luminosity would have been 1.3×10^{52} ergs s^{-1}. These estimates assume $\Omega = 0.2$, $\Lambda = 0$, and $H_0 = 65$ km s^{-1} Mpc^{-1}. Rhoads (1997) has pointed out that one signature of beaming is a steep decay in the afterglow light curve, proportional to t^{-2}. As the initial optical light curve for GRB 991208 indeed appears to decay this steeply, the emission may well be beamed, reducing these estimates.

The current IPN now consists of *Ulysses* and *NEAR* in interplanetary space and numerous near-Earth spacecraft such as *Wind*, *BeppoSAX*, and *CGRO*. The *Mars Surveyor 2001 Orbiter* will join the network in mid-2001. The IPN currently observes ~1–2 GRBs per week and is localizing many of them rapidly to small error boxes. These events tend to be the brighter ones, but apart from this, there is no bias toward any particular event duration; indeed, the IPN generally obtains its smallest error boxes for the short bursts. Neither is there any Sun-angle restriction for the event locations, which means that bursts will be detected whose locations are close to the Sun, as this one was, making prompt radio observations of these positions important. The other advantages of radio observations over optical are the longer lifetime of the radio afterglow, the immunity from weather, and the freedom to operate at any part of the diurnal cycle. This should increase the rate of counterpart detections substantially over the next several years.

K. H. acknowledges support for *Ulysses* operations under JPL Contract 958056, for IPN operations under NASA LTSA grant NAG5-3500, and for *NEAR* operations under the *NEAR* Participating Scientist program. On the Russian side, this work was partially supported by RFBR grant 99-02-17031. We are grateful to R. Gold and R. McNutt for their assistance with the *NEAR* spacecraft. R. S. is supported by NASA grant NCC5-380. We are indebted to T. Sheets for her excellent work on *NEAR* data reduction. Special thanks also go to the *NEAR* project office for its support of postlaunch changes to XGRS software that made these measurements possible. In particular, we are grateful to John Hayes and Susan Schneider for writing the GRB software for the XGRS instrument and to Stanley Cooper and David Tillman for making it possible to get accurate universal time for the *NEAR* GRB detections.

REFERENCES

Aptekar, R., et al. 1995, Space Sci. Rev., 71, 265
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bremer, M., Bertoldi, F., Lisenfeld, U., Castro-Tirado, A., Galama, T., & Kreysa, E. 1999, GCN Circ. 459 (http://gcn.gsfc.nasa.gov/gcn/gcn3/459.gcn3)
Castro-Tirado, A., et al. 1999, GCN Circ. 452 (http://gcn.gsfc.nasa.gov/gcn/gcn3/452.gcn3)
Cline, T., et al. 1999, A&AS, 138, 557
Costa, E., et al. 1997, Nature, 387, 783
Dodonov, S., Afanasiev, V., Sokolov, V., Moiseev, A., & Castro-Tirado, A. 1999, GCN Circ. 475 (http://gcn.gsfc.nasa.gov/gcn/gcn3/475.gcn3)
Frail, D. 1999, GCN Circ. 451 (http://gcn.gsfc.nasa.gov/gcn/gcn3/451.gcn3)
Garnavich, P., & Noriega-Crespo, A. 1999, GCN Circ. 456 (http://gcn.gsfc.nasa.gov/gcn/gcn3/456.gcn3)
Goldsten, J., et al. 1997, Space Sci. Rev., 82, 169
Hurley, K. 1992, in AIP Conf. Proc. 265, Gamma-Ray Bursts, ed. W. Paciesas & G. Fishman (New York: AIP), 3
Hurley, K., et al. 1992, A&AS, 92, 401
———. 1999, GCN Circ. 450 (http://gcn.gsfc.nasa.gov/gcn/gcn3/450.gcn3)
Jensen, B., Hjorth, J., Pedersen, H., Kristen, H., Tomassi, L., Pian, E., & Hurley, K. 1999, GCN Circ. 454 (http://gcn.gsfc.nasa.gov/gcn/gcn3/454.gcn3)
Kouveliotou, C., Meegan, C., Fishman, G., Bhat, N., Briggs, M., Koshut, T., Paciesas, W., & Pendleton, G. 1993, ApJ, 413, L101
Masetti, N., Palazzi, E., Pian, E., Frontera F., Benetti, S., Magazzu, A., Castro-Tirado, A., & Masetti, B. 1999, GCN Circ. 462 (http://gcn.gsfc.nasa.gov/gcn/gcn3/462.gcn3)
Pooley, G. 1999, GCN Circ. 457 (http://gcn.gsfc.nasa.gov/gcn/gcn3/457.gcn3)
Rhoads, J. 1997, ApJ, 487, L1
Shepherd, D., Jogee, S., Kulkarni, S., & Frail, D. 1999, GCN Circ. 455 (http://gcn.gsfc.nasa.gov/gcn/gcn3/455.gcn3)
van Paradijs, J., et al. 1997, Nature, 386, 686