View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Caltech Authors - Main

A Coordinated Radio Afterglow Program

D. A. Frail[1], S. R. Kulkarni[2], M. H. Wieringa[3], G. B. Taylor[1], G. H. Moriarty-Schieven[4], D. S. Shepherd[1], R. M. Wark[3], R. Subrahmanyan[3], D. McConnell[3], and S. J. Cunningham[3]

[1]*National Radio Astronomy Observatory, Socorro, NM 87801*[1]
[2]*Division of Physics, Mathematics, and Astronomy 105-24, Caltech, Pasadena, CA 91125*
[3]*Australia Telescope National Facility, CSIRO, Epping 2121, Australia*
[4]*Joint Astronomy Centre, 600 A'Ohoku Place, Hilo, HI 96720*

Abstract. We describe a ground-based effort to find and study afterglows at centimeter and millimeter wavelengths. We have observed all well-localized gamma-ray bursts in the Northern and Southern sky since BeppoSAX first started providing rapid positions in early 1997. Of the 23 GRBs for which X-ray afterglows have been detected, 10 have optical afterglows and 9 have radio afterglows. A growing number of GRBs have both X-ray and radio afterglows but lack a corresponding optical afterglow.

INTRODUCTION

BeppoSAX revolutionized gamma-ray burst (GRB) astronomy not only through its discovery of X-ray afterglows but also through the dissemination of accurate and timely GRB positions to ground-based observers, who then conduct searches for afterglows at optical and radio wavelengths. Our collaboration uses the interferometer facilities of the Very Large Array (VLA), the Australia Telescope Compact Array (ATCA), the Very Long Baseline Array (VLBA) and the Owens Valley Radio Observatory (OVRO) Interferometer. At high frequencies, we use single dish telescopes which include the James Clerk Maxwell Telescope (JCMT) and the OVRO 40-m Telescope. All afterglow searches begin with the VLA in the northern hemisphere ($\delta > -45°$, $\sigma_{\rm rms} = 45$ μJy in 10 min, FOV $\simeq 5'$) and the ATCA in the southern hemisphere ($\delta < -45°$, $\sigma_{\rm rms} = 45$ μJy in 240 min, FOV $\simeq 5'$), typically at a frequency of 8.5 GHz, which provides a balance between sensitivity and field-of-view. Follow-up programs at the other radio facilities are begun after a VLA or ATCA transient is discovered.

As with quasars, radio observations provide unique diagnostics complementary to those obtained at X-ray and optical wavelengths. Our collaboration has discovered

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

CP526, *Gamma-Ray Bursts: 5th Huntsville Symposium,* edited by R. M. Kippen, et al.
© 2000 American Institute of Physics 1-56396-947-5/00/$17.00

Downloaded 02 Oct 2007 to 131.215.225.176. Redistribution subject to AIP license or copyright, see http://proceedings.aip.org/proceedings/cpcr.jsp

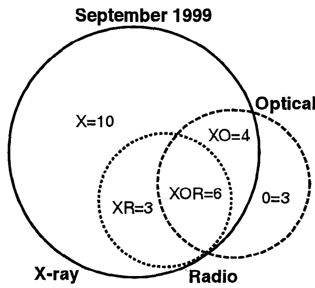

FIGURE 1. A Venn diagram showing the detection statistics for 26 well-localized GRBs. Of the 23 GRBs for which X-ray afterglows have been detected to date, 10 have optical afterglows (XO + XOR) and 9 have radio afterglows (XR + XOR). In total there are 13 optical and/or radio afterglows with corresponding X-ray afterglows (XO + XR + XOR). Only 6 GRBs have afterglows detected in all three bands (XOR).

all known radio afterglows to date, leading to a number of important results: the direct demonstration of relativistic expansion of the ejecta (Frail et al. 1997a), evidence for a reverse shock (Kulkarni et al. 1999), the first true calorimetry of a GRB explosion (Frail, Waxman & Kulkarni 1999), the discovery of optically obscured events (Taylor et al. 1998), the first unambiguous evidence that the ejecta are collimated in jets (Harrison et al. 1999), and the discovery of a possible link between supernovae and GRBs (Kulkarni et al. 1998).

RADIO AFTERGLOW STATISTICS

Since 1997 we have observed 19 GRBs with the VLA and detected a total of eight radio afterglows (see Figure 1, Tables 1 and 2). The peak fluxes (F_{peak}) of the detections range from 1200 μJy to 150 μJy. This small range of F_{peak} values suggests that our ability to detect radio afterglows is severely limited by the sensitivity of the telescope. The "lifetime" (i.e., t_{max}) of the radio afterglows is signal-to-noise limited but it is clear, at least among bursts of comparable brightness, that t_{max} varies substantially. Of special note are the three GRBs (970828, 981226, and 990506) which have no optical counterparts (i.e., XR class). These may represent an important group of GRBs whose optical emission is extincted by dust.

There are 11 GRBs for which a VLA search of the error box failed to detect a radio afterglow (see Table 2). The peak fluxes given in the table are conservative upper limits for a radio afterglow on a time-scale of 1 to 30 days and at frequencies between 1.4 and 8.5 GHz. These non-detections vary in quality depending on the size of the error circle but most observations had sufficient sensitivity to detect radio afterglows with fluxes comparable to those listed in Table 1.

Downloaded 02 Oct 2007 to 131.215.225.176. Redistribution subject to AIP license or copyright, see http://proceedings.aip.org/proceedings/cpcr.jsp

TABLE 1. Radio Afterglow Detections.

GRB	F_{peak} (μJy)	t_{max} (days)	AG Class	Instruments	References
970508	1200	450	XOR	VLA, VLBA, OVRO, JCMT	Frail et al. (1997a)
970828	150	3.5	XR	VLA	Djorgovski et al. (1999)
980329	300	135	XOR	VLA, OVRO, JCMT	Taylor et al. (1998)
980425[a]	50,000	>300	XOR	ATCA, JCMT	Kulkarni et al. (1998)
980519	300	65	XOR	VLA, OVRO	Frail et al. (1999a)
980703	1200	210	XOR	VLA, VLBA, JCMT	Bloom et al. (1998)
981226	170	20	XR	VLA	Frail et al. (1999b)
990123	260	1.2	XOR	VLA, OVRO, OVRO 40-m, JCMT	Kulkarni et al. (1999)
990506	550	<16	XR	VLA	Taylor et al. (1999)
990510	225	20	XOR	ATCA	Harrison et al. (1999)

[a] Related to SN1998bw. We do not include this GRB in the detection statistics.

TABLE 2. VLA Afterglow Non-Detections.

GRB	F_{peak} (μJy)	AG Class	References
970111	<300	X	Frail et al. (1997b)
970228	<50	XO	Frail et al. (1998)
970616	<150	X	IAUC #6691
970815	<50	X	IAUC #6723
971214	<25	XO	Ramaprakash et al. (1998)
971227	<50	X	
980326	<150	O	
980613	<50	XO	
981220	<125	X	GCN #269
990520	<125	X	
990704	<125	X	

TABLE 3. ATCA Afterglow Non-Detections.

GRB	F_{peak} (μJy)	AG Class	References
970402	<300	X	
980109	<550	[a]	
990217	<175	[a]	GCN #266
990627	<125	X	GCN #357
990705	<100	XO	GCN #376
990712	<100	O	

[a] GRB 990109 and 990217 were seen only in gamma-rays. No afterglows were detected at any wavelength.

There have been two radio afterglow detections made at the ATCA (see Table 1). The possible relation of GRB 980425 to SN1998bw makes it a rather unusual event, so we do not include it in the detection statistics. The upper limits of the six ATCA non-detections in Table 3 were not sufficient to have detected the weaker

Downloaded 02 Oct 2007 to 131.215.225.176. Redistribution subject to AIP license or copyright, see http://proceedings.aip.org/proceedings/cpcr.jsp

radio afterglows in Table 1.

SUMMARY

In summary, our coordinated program has been very successful in detecting radio afterglows from GRBs. In particular:

- Six gamma-ray bursts are seen at X-ray, optical and radio wavelengths (GRB 970508, GRB 980329, GRB 980519, GRB 980703, GRB 990123, GRB 990510) (see Figure 1).
- Of the 23 X-ray afterglows, nine have been detected at radio wavelengths (XOR + XR) for a rate of 39%. At the VLA the detection rate is 8/19 or 42%. The small range in the observed peak flux densities suggests that our ability to detect radio afterglows is mainly limited by the sensitivity of the telescopes (VLA and ATCA).
- Of the 23 X-ray afterglows, ten have been detected at optical wavelengths (XOR + XO) or 43%. The detection rate of well-localized GRBs is comparable at optical and radio wavelengths.
- There exists a growing class (XR) of "dark" GRBs which have X-ray and radio afterglows but no known optical afterglow. These may represent an important group of GRBs whose optical emission is extincted by dust.

REFERENCES

1. Bloom, J. S., Frail, D. A., Kulkarni, S. R., Djorgovski, S. G., Halpern, J. P., Marzke, R. O., Patton, D. R., Oke, J. B., Horne, K. D., Gomer, R., Goodrich, R., Campbell, R., Moriarty-Schieven, G. H., Redman, R. O., Feldman, P. A., Costa, E., and Masetti, N. The Discovery and Broadband Follow-up of the Transient Afterglow of GRB 980703. *ApJ* **508**, L21–L24, (1998).
2. Djorgovski, S. G., et. al. The radio afterglow from GRB 970828 and optical spectroscopy of its host galaxy. ApJ (Letters) submitted, (1999).
3. Frail, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M., and Taylor, G. B. The radio afterglow from the gamma-ray burst of 8 May 1997. *Nature* **389**, 261–263, (1997a).
4. Frail, D. A., Kulkarni, S. R., Costa, E., Frontera, F., Heise, J., Feroci, M., Piro, L., Dal Fiume, D., Nicastro, L., Palazzi, E., and Jager, R. Radio Monitoring of the 1997 January 11 Gamma-Ray Burst. *ApJ* **483**, L91–L94, (1997b).
5. Frail, D. A., Kulkarni, S. R., Shepherd, D. S., and Waxman, E. No Radio Afterglow from the Gamma-Ray Burst of 1997 February 28. *ApJ* **502**, L119–L122, (1998).
6. Frail, D. A., Kulkarni, S. R., Sari, R., Taylor, G. B., Shepherd, D. S., Bloom, J. S., Young, C. H., Nicastro, L., and Masetti, N. The radio afterglow from GRB 980519: A test of the jet and circumstellar models. ApJ submitted; astro-ph/9910060, (1999a).

Downloaded 02 Oct 2007 to 131.215.225.176. Redistribution subject to AIP license or copyright, see http://proceedings.aip.org/proceedings/cpcr.jsp

7. Frail, D. A., Kulkarni, S. R., Bloom, J. S., Djorgovski, S. G., Gorjian, V., Gal, R. R., Meltzer, J., Sari, R., Chaffee, F. H., Goodrich, R. W., Frontera, F., and Costa, E. The radio afterglow and the host galaxy of the x-ray rich GRB 981226. ApJ (Letters) in press; astro-ph/9909407, (1999b).
8. Frail, D. A., Waxman, E., and Kulkarni, S. R. A 450-day light curve of the radio afterglow of GRB 970508: Fireball calorimetry. ApJ (Letters) submitted; astro-ph/9910319, (1999).
9. Harrison, F. A., Bloom, J. S., Frail, D. A., Sari, R., Kulkarni, S. R., Djorgovski, S. G., Axelrod, T., Mould, J., Schmidt, B. P., Wieringa, M. H., Wark, R. M., Subrahmanyan, R., McConnell, D., McCarthy, P. J., Schaefer, B. E., McMahon, R. G., Markze, R. O., Firth, E., Soffitta, P., and Amati, L. Optical and Radio Observations of the Afterglow from GRB 990510: Evidence for a Jet. *ApJ* **523**, L121–L124, (1999).
10. Kulkarni, S. R., Frail, D. A., Wieringa, M. H., Ekers, R. D., Sadler, E. M., Wark, R. M., Higdon, J. L., Phinney, E. S., and Bloom, J. S. Radio emission from the unusual supernova 1998bw and its association with the gamma-ray burst of 25 April 1998. *Nature* **395**, 663–669, (1998).
11. Kulkarni, S. R., Frail, D. A., Sari, R., Moriarty-Schieven, G. H., Shepherd, D. S., Udomprasert, P., Readhead, A. C. S., Bloom, J. S., Feroci, M., and Costa, E. Discovery of a Radio Flare from GRB 990123. *ApJ* **522**, L97–L100, (1999).
12. Ramaprakash, A. N., Kulkarni, S. R., Frail, D. A., Koresko, C., Kuchner, M., Goodrich, R., Neugebauer, G., Murphy, R., Eikenberry, S., Bloom, J. S., Djorgovski, S. G., Waxman, E., Frontera, F., Feroci, M., and Nicastro, L. The energetic afterglow of the gamma-ray burst of 14 December 1997. *Nature* **393**, 43–46, (1998).
13. Taylor, G. B. *et al.* The Discovery of the Radio Afterglow from the Optically Dim Gamma-Ray Burst of 1998 March 29. *ApJ* **502**, L115, (1998).
14. Taylor, G. B. *et al.* The gamma-ray burst of 1999 May 6 and the population of optically dim afterglows. In preparation, (1999).

Downloaded 02 Oct 2007 to 131.215.225.176. Redistribution subject to AIP license or copyright, see http://proceedings.aip.org/proceedings/cpcr.jsp