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THE INTERPLANETARY NETWORK SUPPLEMENT TO THE *BeppoSAX* GAMMA-RAY BURST CATALOGS

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ABSTRACT

Between 1996 July and 2002 April, one or more spacecraft of the interplanetary network detected 786 cosmic gamma-ray bursts that were also detected by the Gamma-Ray Burst Monitor and/or Wide-Field X-Ray Camera experiments aboard the *BeppoSAX* spacecraft. During this period, the network consisted of up to six spacecraft, and using triangulation, the localizations of 475 bursts were obtained. We present the localization data for these events.

Key words: astronomical databases: miscellaneous – catalogs – gamma-ray burst: general – techniques: miscellaneous

Online-only material: machine-readable tables

1. INTRODUCTION

Between 1996 July and 2002 April, the Wide Field X-Ray Camera (WFC) and Gamma-Ray Burst Monitor (GRBM) aboard the *BeppoSAX* mission detected 62 and 1092 cosmic gamma-ray bursts (GRBs), respectively, and localized many of them to accuracies which ranged from arcminutes to tens of degrees (Vetere et al. 2007; Frontera et al. 2009; instrument descriptions may be found in Feroci et al. 1997, Frontera et al. 1997, and Jager et al. 1997). These detections were used to initiate searches through the data of the spacecraft comprising the interplanetary network (IPN). In 475 cases, localizations could be obtained by triangulation, and successful multiwavelength counterpart searches were initiated for some of them. The IPN contained between four and six spacecraft during this period. They were, in addition to *BeppoSAX*: *Ulysses,* in heliocentric orbit at distances between 670 and 3180 lt-s from Earth (Hurley et al. 1992); *Konus-Wind*, in various orbits up to around 4 lt-s from Earth (Aptekar et al. 1995); *HETE-II-FREGATE*, in low Earth orbit (Ricker et al. 2003; Atteia et al. 2003); the *Near-Earth Asteroid Rendezvous* (*NEAR*) mission, at distances up to 1300 lt-s from Earth (Trombka et al. 1999); *Mars Odyssey*, launched in 2001 April and in orbit around Mars starting in 2001 October, up to 1250 lt-s from Earth (Hurley et al. 2006); the *Compton Gamma-Ray Observatory* (the Burst and Transient Source Experiment (BATSE); Fishman et al. 1992); and *RHESSI* both in low Earth orbit (Smith et al. 2002). Their timelines are presented in Figure 1. In this paper, we present the localization data obtained by the IPN for these bursts. An initial description of this work was given in Hurley et al. (2000b).

At least three other spacecraft recorded GRB detections during this period, although they were not used for triangulation and therefore were not, strictly speaking, part of the IPN. The *Rossi X-Ray Timing Explorer* (*RXTE*) All Sky Monitor detected and localized some *BeppoSAX* bursts (Smith et al. 1999). It operated in the low-energy X-ray range, where the light curves of GRBs differ significantly from the high-energy range where the other IPN instruments operate. The *Defense Meteorological Satellite Program* (*DMSP*; Terrell et al. 1996, 1998; Terrell & Klebesadel 2004) and the *Stretched Rohini Satellite Series* (*SROSS*; Marar et al. 1994) spacecraft also detected, but did not localize, bursts. As they were in low Earth orbit, they were at distances of several tens of light-milliseconds from *BeppoSAX*, and their data were redundant as far as triangulation was concerned.

2. OBSERVATIONS

For each GRB detected by *BeppoSAX*, a search was initiated in the data of the IPN spacecraft. For the spacecraft within a few light-seconds of Earth, the search window was centered on the *BeppoSAX* trigger time, and its duration was somewhat greater than the event duration. For the spacecraft at interplanetary distances, the search window was twice the light-travel time to the spacecraft if the event arrival direction

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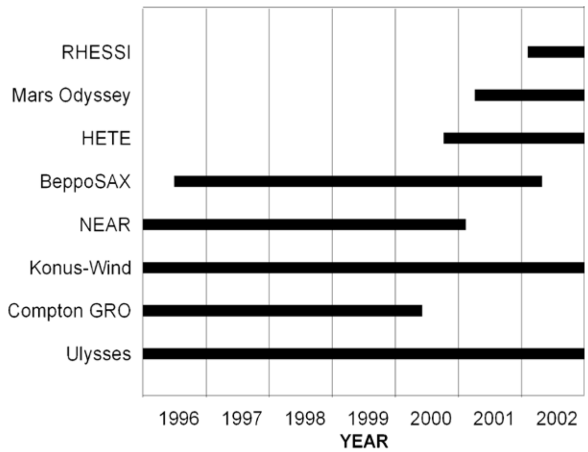

Figure 1. Timelines of the missions comprising the interplanetary network between 1996 and 2002. During the period when *BeppoSAX* was operational, there were a minimum of three and a maximum of five other missions in the network. There were two interplanetary spacecraft in operation for most of the *BeppoSAX* mission, *Ulysses* and either *NEAR* or *Odyssey*.

Table 1
IPN/*BeppoSAX* Gamma-ray Bursts

Designation[a]	Date	Universal Time[b]	Observed by[c]
GRB960703A	1996 Jul 3	07:39:48	Kon
GRB960703B	1996 Jul 3	13:42:53	Uly, BAT, Kon
GRB960703C	1996 Jul 3	18:10:40	BAT, Kon, SRS
GRB960707A	1996 Jul 7	10:16:40	Uly, BAT, Kon
GRB960707B	1996 Jul 7	16:26:04	BAT
GRB960720	1996 Jul 20	11:36:53	BAT, Kon
GRB960723A	1996 Jul 23	04:46:01	BAT, Kon
GRB960725	1996 Jul 25	17:39:07	BAT
GRB960730	1996 Jul 30	19:35:08	BAT, Kon
GRB960731	1996 Jul 31	05:46:01	Uly, BAT, Kon

Notes.
[a] This is the *BeppoSAX* designation in Frontera et al. (2009) or Vetere et al. (2007); designations in other catalogs may differ.
[b] Universal time is the Earth-crossing time of the start of the event.
[c] DMS: *Defense Meteorological Satellite Program*; HET: *HETE-II*; Kon: *Konus-Wind*; MO: *Mars Odyssey*; NEA: *Near Earth Asteroid Rendezvous* mission; RHE: *RHESSI*; SRS: *Stretched Rohini Satellite Series*; Uly: *Ulysses*; XTE: *Rossi X-Ray Timing Explorer.*

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

was unknown, which was the case for most events. If the arrival direction was known, even coarsely, the search window was defined by calculating the expected arrival time at the spacecraft, and searching in a window around it. Of the approximately 3300 events detected by one or more IPN spacecraft while *BeppoSAX* was operational, 786 were also detected by *BeppoSAX*; these are listed in Table 1, with the following abbreviations: DMS: *Defense Meteorological Satellite Program*, HET: *HETE-II*, Kon: *Konus-Wind*, MO: *Mars Odyssey*, NEA: *Near Earth Asteroid Rendezvous* mission, RHE: *RHESSI*, SRS: *Stretched Rohini Satellite Series*, Uly: *Ulysses*, XTE: *Rossi X-Ray Timing Explorer*. The burst designation in Table 1 follows that of Frontera et al. (2009) or Vetere et al. (2007), and in some cases it differs from designations in other catalogs. Table 2 shows the number of events observed by each spacecraft in the IPN, and Table 3 gives the number of bursts that were detected by a total of N spacecraft, where N is between 2 and 6. In these tables, detections by *RXTE*, *DMSP*, and *SROSS* have been counted for completeness.

3. LOCALIZATIONS

When a GRB arrives at two spacecraft with a delay δT, it may be localized to an annulus whose half-angle θ with respect to the vector joining the two spacecraft is given by

$$\cos\theta = \frac{c\delta T}{D}, \tag{1}$$

where c is the speed of light and D is the distance between the two spacecraft. (This assumes that the burst is a plane wave, i.e., that its distance is much greater than D.) The annulus width $d\theta$, is

$$d\theta = c\sigma(\delta T)/D\,\sin\theta, \tag{2}$$

where $\sigma(\delta T)$ is the uncertainty in the time delay. $\sigma(\delta T)$ is generally of the order of 100 ms or more, when both statistical and systematic uncertainties are considered; thus triangulation between two near-Earth spacecraft, for which D/c is at most $\sim$40 ms, does not constrain the burst arrival direction significantly. When D/c is of the order of several light-seconds (e.g., the distance between *Konus-Wind* and a near-Earth spacecraft), annuli with widths of several degrees or less can be obtained; when D/c is several hundred light-seconds or more (i.e., an interplanetary spacecraft and a near-Earth spacecraft), annulus widths of the order of arcminutes or less are possible. When two interplanetary spacecraft and a near-Earth spacecraft observe a GRB, a small error box can be obtained. Table 4 gives the number of events observed by 0, 1, and 2 interplanetary spacecraft.

Four hundred and seventy-five bursts could be localized by the method above; Table 5 gives the localization information for them. Triangulation annuli are given in the four IPN columns: these are the right ascension and declination of the annulus center α, δ, the annulus radius R, and the uncertainty in the radius δR. One or two annuli are specified. In addition to triangulation annuli, several other types of localization information are included in this catalog. The three BATSE columns give the right ascension, declination, and 1σ (statistical only) error radius of the BATSE localizations, where they are available. These are taken from the current catalog on the BATSE Web site[17] as well as from the BATSE untriggered burst catalogs (Stern et al. 2001; Kommers et al. 2000). Three SAX columns give the right ascension, declination, and 90% confidence radius of the *BeppoSAX* localization, either from the GRBM or the WFC catalog (Frontera et al. 2009; Vetere et al. 2007). As the Vetere et al. (2007) catalog does not contain error radii for the WFC bursts, these have been obtained from the IAU and GCN Circulars. Although all the bursts in Table 5 were detected by *BeppoSAX*, not all of them could be localized by the WFC or GRBM. The three *HETE* columns give the right ascension, declination, and radius of the Wide Field X-Ray Monitor error circle (R. Vanderspek et al. 2010, in preparation). Combining these error circles with the IPN annuli often results in smaller error regions. IPN localizations for almost all bursts with a BATSE or *HETE* error circle have appeared in a previous catalog and are repeated here only for completeness.

The two Ecliptic columns give the ecliptic latitudes of the bursts, measured northward (positive) from the ecliptic plane towards the north ecliptic pole. These are derived by comparing

[17] http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/

Table 2
Number of *BeppoSAX* Bursts Observed by Each Spacecraft

BATSE	*DMSP*	*HETE*	*Konus*	*NEAR*	*Odyssey*	*RHESSI*	*RXTE*	*SROSS*	*Ulysses*
426	14	14	528	152	13	10	9	5	376

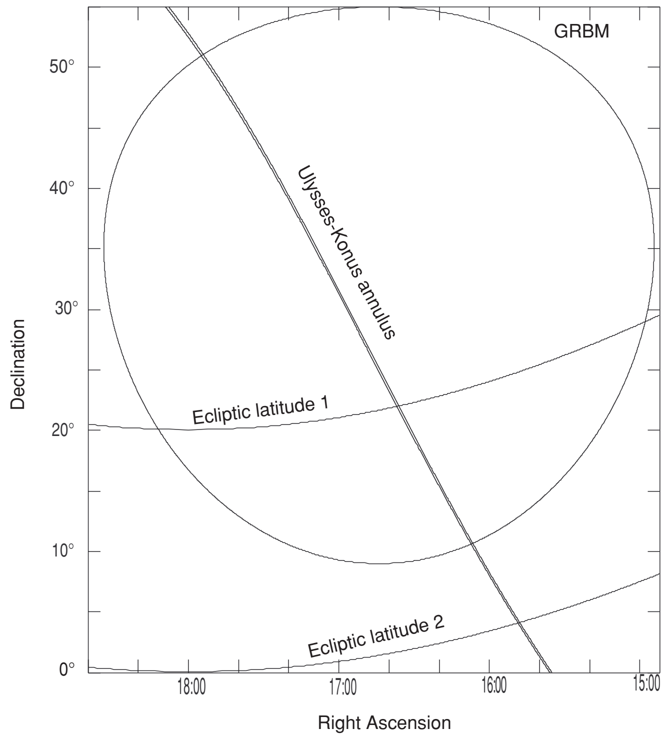

Figure 2. Localizations of GRB970203. The arrival direction is defined by the intersection of the 33° radius GRBM error circle, the 0°.16 wide IPN annulus, and the 20° wide *Konus* ecliptic latitude band.

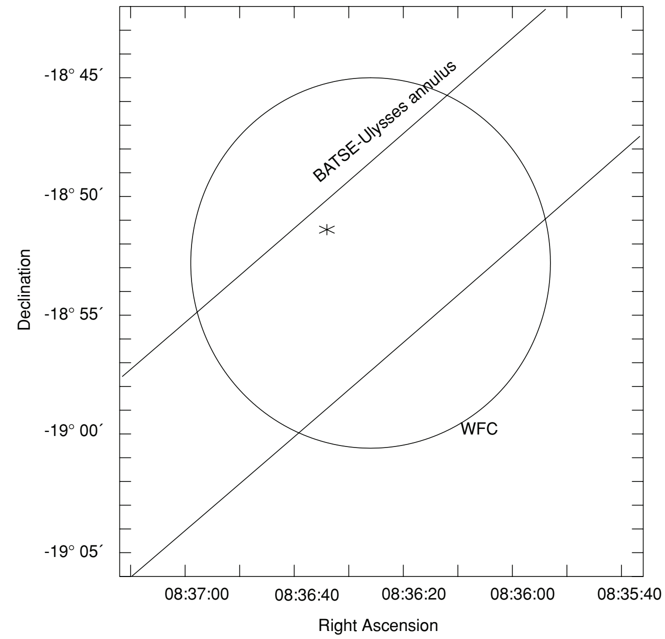

Figure 3. Localizations of GRB980326. The arrival direction is defined by the intersection of the 0°.133 radius WFC error circle and the 0°.092 wide BATSE-*Ulysses* annulus. The initial WFC and IPN localizations were announced in Celidonio et al. (1998) and Hurley et al. (1998). The optical counterpart, indicated by an asterisk, was found by Groot et al. (1998).

Table 3
Number of *BeppoSAX* Bursts in this Catalog Observed by a Total of *N* Experiments, Regardless of their Distance from Earth

$N = 1$	2	3	4	5	6
0	324	220	196	40	7

Table 4
Number of *BeppoSAX* Bursts Observed by *N* Interplanetary Spacecraft, i.e., *NEAR*, *Mars Odyssey*, and *Ulysses*

$N = 0$	1	2
362	309	116

the count rates of the two *Konus-Wind* detectors (Aptekar et al. 1995). The axis of one detector points towards the north ecliptic pole, and the axis of the other points toward the south ecliptic pole. In addition to statistical uncertainties, the ecliptic latitude determination is subject to systematic uncertainties due to, among other things, time-variable cosmic X-ray sources and absorption by other instruments aboard the spinning *Wind* spacecraft. The numbers given here can be taken to be at the 90%–95% confidence level. Planet-blocking is specified by the right ascension and declination of the planet's center and its radius, in the three Planet columns. When a spacecraft in low Earth or Mars orbit observes a burst, the planet blocks up to ≈3.7 sr of the sky. This is often useful for deciding which of two annulus intersections is the correct one, or for eliminating portions of a single annulus. The Other column gives the right ascension, declination, and radius of any other localization region, which may be obtained in one of several ways. In some cases, the burst was observed by four spacecraft which were separated by large enough distances to give three triangulation annuli, whose intersections are consistent with a single error box. In other cases, the anisotropic response of one of the IPN experiments allows the ambiguity to be resolved. In still other cases, a region may be derived from planet blocking by a second spacecraft in addition to the data in the Planet column. In this case, the error circle given is the complement of the planet-blocking circle, that is, a circle whose right ascension is the right ascension of the planet plus 180°, whose declination is the negative of the planet's declination, and whose radius is 180° minus the planet's angular radius. The units of the entries in Table 5 are in degrees, and all coordinates are J2000. The last column gives the approximate localization area in square degrees. This is the area of the region which is common to all the localizations. For bursts where the *BeppoSAX* or BATSE error circle does not intersect the IPN annulus, the area given is that of the annulus alone. Figures 2 and 3 show examples of coarse and fine IPN localizations.

For some events, no triangulation was possible, but coarse constraints on the burst arrival direction can be derived from planet blocking, ecliptic latitudes, or both. This information is not given here, but information on these events, as well as the ones in this catalog, may be found at the IPN Web site.[18]

As for BATSE, the *BeppoSAX* GRBM localizations are derived by comparing the count rates of various detectors

[18] ssl.berkeley.edu/ipn3/index.html

Table 5
IPN Localization Data

		BATSE			SAX			*HETE*			IPN				Ecliptic		Planet			Other			Area
Date	UT	α	δ	R	α	δ	R	α	δ	R	α_1	δ_1	R_1	δR_1	β_1	β_2	α	δ	R	α	δ	R	(sq. deg.)
											α_2	δ_2	R_2	δR_2									
1996 Jul 3	13:42:53	4.6	−7.8	1.0	...	...	...	...	...	...	334.713	−46.652	46.702	.136	...	...	...	...	...	...	...	...	1.09E+00
1996 Jul 7	10:16:40	321.0	82.5	1.1	...	...	...	...	...	...	155.435	45.862	50.112	.027	...	...	...	...	...	...	...	...	1.63E-01
1996 Jul 31	05:46:01	43.9	12.5	.9	...	...	...	...	...	...	340.144	−41.403	83.839	.012	...	...	...	...	...	...	...	...	9.28E+00
1996 Aug 1	11:29:09	...	...	...	...	...	...	...	...	...	340.436	−41.223	78.075	.099	−9.8	10.2	...	...	...	...	...	...	1.01E+01
1996 Aug 5	21:55:57	...	...	...	...	...	...	...	...	...	161.328	40.481	74.569	.012	57.3	77.3	223.8	3.8	66.1	...	...	...	5.83E-01
											161.301	40.450	74.588	.023									
1996 Aug 10	06:56:16	...	...	...	102.000	−11.000	33.000	...	...	...	162.208	39.772	82.350	.004	−48.5	−28.5	...	...	...	...	...	...	3.75E-02
											151.487	9.968	52.713	2.844									
1996 Aug 25	00:23:03	...	...	...	...	...	...	...	...	...	165.211	37.557	57.225	.013	72.3	90.0	...	...	...	...	...	...	1.49E+00
											165.193	37.542	57.249	.009									

Note. [a] IPN annulus does not include *BeppoSAX* localization.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 6
IPN Catalogs of Gamma-ray Bursts

Years Covered	Number of GRBs	Description
1990–1992	16	*Ulysses, Pioneer Venus Orbiter,* WATCH, SIGMA, PHEBUS GRBs[a]
1990–1994	56	*Granat*-WATCH supplement[b]
1991–1992	37	*Pioneer Venus Orbiter, Compton Gamma-Ray Observatory, Ulysses* GRBs[c]
1991–1994	218	BATSE 3B supplement[d]
1991–2000	211	BATSE untriggered burst supplement[e]
1992–1993	9	*Mars Observer* GRBs[f]
1994–1996	147	BATSE 4Br supplement[g]
1996–2000	343	BATSE 5B supplement[h]
1996–2002	475	*BeppoSAX* supplement[i]
2000–2006	226	HETE-2 supplement[j]

Notes. [a] Hurley et al. (2000a). [b] Hurley et al. (2000c). [c] Laros et al. (1998). [d] Hurley et al. (1999a). [e] Hurley et al. (2005a). [f] Laros et al. (1997). [g] Hurley et al. (1999b). [h] Hurley et al. (2005b). [i] Present catalog. [j] Hurley et al. (2009).

aboard these spacecraft. These localizations are affected by Earth albedo and absorption by spacecraft materials, among other things, and their shapes are in general complex. The error circles are approximations to these shapes. They are centered at the point which is the most likely arrival direction for the burst, and their radii are defined so that their areas are equal to the 1σ (BATSE) or 90% confidence (*BeppoSAX* GRBM) statistical-only true error regions. Therefore in some cases, indicated by a footnote, the IPN annuli do not cross the error circles. This occurs for 25 of the 133 *BeppoSAX* GRBM localizations in this catalog. We have examined the true *BeppoSAX* error regions in all of these cases and have verified that they are indeed consistent with the IPN annuli. In some of these cases, an error circle has been defined in the "Other" column which limits the IPN annulus or annuli to a region which, from a consideration of all the available data, is known to define the arrival direction. Thus for those bursts where the GRBM error circle does not intersect the IPN annulus, the "Other" circle should be used in place of the GRBM circle.

4. COMMENTS ON SPECIFIC EVENTS

GRB960916B at 03:56:20 may be the same event as GRB960916A in the *BeppoSAX* catalog (Frontera et al. 2009). GRB960916A occurred 312 s earlier, at 03:51:08, and it was detected by *Konus-Wind*, but not by *Ulysses*. This non-detection is consistent with the fact that the earlier event was weaker. The *Konus* ecliptic latitudes for these two events are consistent with a single origin, i.e., a very long burst.

GRB970315B at 22:09:19 may be from the same source as BATSE 6125 at 22:13:42.[19] The IPN annulus passes through the BATSE error circle, and the duration of the BATSE event is given as 1307 s. BeppoSAX entered the SAA at 22:10:09, so it could not observe the BATSE event, and the BATSE position of the event was Earth-occulted to BATSE at the time of the BeppoSAX event. If these are indeed from a single source, the total duration would have been around 1570 s. *Ulysses* did not observe any emission which would be consistent with the BATSE burst, but this is consistent with its lower intensity.

GRB970415 was observed as a very weak event by *Ulysses*, and reliable triangulation of it is not possible.

GRB970518 has a duration of approximately 370 s. The GRBM observed only the later part of the event, at 07:12:12. However, the burst started at 07:06:23, and this is the time given in Tables 1, 5, and 6.

[19] http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/

GRB971228B at 14:53:52, GRB990516A at 20:55:15, and GRB990905 at 22:38:55 were observed as very weak events by *Ulysses*, and reliable triangulation of them is not possible.

GRB991026B has an IPN localization which is inconsistent with the final *BeppoSAX* WFC localization in Vetere et al. (2007). The minimum distance between the IPN annulus and the WFC position is about $4.^{\circ}8$ (no uncertainty is given for the WFC localization). The WFC position given in Table 5 is from J. in't Zand (2004, private communication), and is consistent with the IPN localization.

GRB991030 has an IPN localization which is inconsistent with the *BeppoSAX* WFC localization in Vetere et al. (2007). The minimum distance between the IPN annulus and the WFC position is about $5.^{\circ}9$ (no uncertainty is given for the WFC localization). The WFC position given in Table 5 is from J. in't Zand (2004, private communication), and is consistent with the IPN localization.

GRB000629B does not appear in the *BeppoSAX* catalog, because it was initially thought to be solar. Analysis of the *Konus-Wind* data, however, points to a likely cosmic origin.

GRB011221 triggered the GRBM just prior to entry into the South Atlantic Anomaly. All GRBM data were lost, and this burst does not appear in the *BeppoSAX* catalog.

5. CONCLUSIONS

This is the tenth in a continuing series of IPN catalogs, summarized in Table 6; the localization data for all of them can be found in electronic form at the IPN Web site. The IPN is, in effect, a full-time, all-sky monitor, when the duty cycles and viewing constraints of all its instruments are considered. Its fluence and flux thresholds for 50% detection efficiency are about 6×10^{-7} erg cm^{-2} and 1 photon cm^{-2} s^{-1}, respectively. Over the *BeppoSAX* mission, 786 bursts were detected by the GRBM and/or the WFC and at least one other IPN instrument and 475 of them could be localized to some extent by triangulation. The more precise and/or rapid localizations were announced in over 50 IAU and GCN Circulars (in 1997, and in 1998–2002, respectively), resulting in multiwavelength counterpart searches. Regardless of the precision and speed of the localizations, however, burst data such as these are useful for numerous studies, such as searching for indications of activity from previously unknown soft gamma repeaters, associating supernovae with bursts, or searching for neutrino and gravitational radiation associated with bursts.

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