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Letter to the Editor

Millimetre detection of GRB 970508

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Abstract. The γ-ray burst source GRB 970508 has been detected as a continuum point source at 86.2 GHz with the IRAM Plateau de Bure Interferometer (PdBI). By combining the UV tables of May 17th, 19th, 21st and 22nd, one obtains a point source flux of 1.62 ± 0.25 mJy, which amounts to a 6.5σ detection. Three individual tentative detections were made on May 19-22, and the source was only non-detected later with 3σ upper limits between 0.87 and 1.83 mJy. Observations at 232 GHz gave only upper limits. The lowest one from combined May 19 and 21 data is 4.5 mJy (3σ). No significant variation of the source during individual observing dates was seen in either frequency band. Comparing the May 17-22 detection with the later non-detections, we see a significant fading which is not well fitted with the $F \propto t^{-1.1\pm0.1}$ law found at higher frequencies.

We exclude that the 86.2 GHz fluxes have been modulated significantly by interstellar scintillation. This indicates that the millimetre characteristics of GRB 970508 provide a new aspect of the intrinsic development of the source.

Key words: Gamma-ray bursts – GRB 970508 – radio continuum observations

1. Introduction

Since their discovery with the *Vela* satellites by the end of the 1960's (Klebesadel et al. 1973), γ-ray bursts have intrigued the astronomical community. Their durations range from about 30 ms to more than 1000 s (see Fishman and Meegan 1995 for a review), and during this short time they can be the most prominent γ-ray sources in the sky. However, the lack of angular resolution in the detections and their short lifetime made it impossible to identify their counterparts in other wavelengths.

Previous efforts to detect such counterparts in deep optical imaging of GRB error boxes were not made sufficiently rapid after the GRBs (Vrba et al. 1995, Hudec 1995), partly in the hope to identify quiescent bursters by unusual properties. Observations of GRBs detected with the BATSE experiment using automated telescopes alerted through the BACODINE system (delays of a few seconds) have not yet led to the detection of optical counterparts in excess of $\sim$ 11th magnitude (Park et al. 1997). 3σ upper limits for millimetric GRB fluxes from COBE were 645 Jy at 90 GHz for strong bursts (Ali et al. 1997), and 3.6 mJy at 95 GHz with the BIMA for sources with small positional errors (Gruendl et al. 1997).

Recently, the search for counterparts in other wavelengths has been successful. The deciding step was provided by the Italian/Dutch satellite BeppoSAX (Boella et al. 1997). Its Gamma-Ray Burst Monitor (GRBM) (Frontera et al. 1997) can detect GRBs in the range 60-600 keV, for some of which the X-ray emission is detected simultaneously with one of the two Wide Field Cameras (FoV $40 \times 40^\circ$, Jager et al. 1997).

GRB 970228 was the first event for which X-ray (Costa et al. 1997a) and optical (Van Paradijs et al. 1997; Galama et al. 1997a) afterglows were detected. HST observations of the optical counterpart (Sahu et al. 1997) showed that it consisted of a fading point source embedded in an extended ($\sim 1''$) object, most likely a host galaxy but with a few percent probability a chance superposition (Van Paradijs et al. 1997).

The first unambiguous evidence for the 'cosmological' distance scale of γ-ray bursts was found for GRB 970508. The BeppoSAX GRBM detected a weak burst on May 8.904 UT lasting about 15 s, whose position was determined to $5'$ with the WFC (Costa et al. 1997b). Follow-up observations of this error box led to the detections of X-ray (Piro et al. 1997) and optical (Bond 1997) afterglows. Metzger et al. (1997a,b) placed the redshift of the source between $0.853 < z < 2.3$ from absorption line spectra. On May 13, the source was detected at 8.46 GHz with the VLA ($F = 430 \pm 30 \mu$Jy, Frail et al. 1997a,b). In the following weeks, GRB 970508 was closely monitored by numerous observations in all wavebands.

2. Plateau de Bure Observations

For the observations (see Table 1) with the PdBI (Guilloteau et al. 1992), we used the GRB's position derived at 8.46 GHz by Frail et al. (1997a), which is $\alpha = 06^{\rm h}53^{\rm m}49\overset{\rm s}{.}45$, $\delta = +79^\circ 16' 19\overset{''}{.}5$ (Eq. 2000.0, error in both coordinates $0\overset{''}{.}1$). The SIS dual frequency receivers were operated with bandwidths of 460 MHz using the tuning of the previously scheduled projects to get more time on-source. During clear sky conditions the atmospheric phase correction was used to improve the signal to noise ratio.

The flux of GRB 970508 was estimated relative to the phase calibrator 0716+714 ($F_{86.2\,\rm GHz} = 0.80$ Jy) for comparable atmospheric phase decorrelations, whose flux was derived relative to MWC 349 and 3C273 during the observing dates with the lowest amounts of precipitable water. As 0716+714 is known for rapid variability in the optical and cm range (10-20% over 4-12 hours, see Wagner et al. 1996, Quirrenbach et al. 1991), special care was taken to verify the flux calibration each day relative to one or more other sources. Between May 18 and 28, its maximum day-to-day variation was below 7%, and no significant source-intrinsic variation was detected during individual observations. Only on May 17, a 14% increase was derived relative to 3C454.3, but the conditions for this calibration were marginal so that the observations are consistent with a constant flux for 0716+714 during May 17-28. On August 12, the flux of 0716+714 was found to have increased to 1.24 Jy relative to MWC349 and NRAO530.

Observations at 232 GHz were done in parallel but resulted only in upper limits for GRB 970508. Calibration was relative to a MWC 349 flux of 1.56 Jy and a 3C273 flux of 20.5 Jy at this frequency.

Individual dates were checked for variations in the GRB flux level to assure that the detections did not come from high fluxes during short time intervals, which might have been subsequently "spread" over the observing time. No such variations were detected within the error limits, neither in the 86.2 GHz flux levels, nor in the non-detections at 86.2, 87.76, 86.0 and 232 GHz. The decorrelation factors of the May 17-22 observations are similar, which allows to combine their UV tables (without position shifting) after the appropriate adjustments for the slightly different frequencies. Because central positions of low-σ detections move around statistically, the UV fit positions were released for the flux determination. The result is position offsets: $\Delta\alpha = -0\overset{''}{.}7$, $\Delta\delta = 0\overset{''}{.}4$; $F_{86.2\,\rm GHz} = 1.62 \pm 0.25$ mJy.

3. Discussion

To place the IRAM detection in the context of other observations in the millimetre, optical and centimetre range, we plot a compilation of the reported fluxes and 3σ upper limits during May 1997 in Fig. 1.

Gruendl et al. (1997) observed the source with the BIMA at 85 GHz, and the OVRO was used by Shepherd et al. (1997) at 86.8 GHz. First upper limits by BIMA ($1\sigma = 10$ mJy on May 10.2) and OVRO ($1\sigma = 3.6$ mJy on May 11.1) are outside the range of the uppermost plot but constrain the early development of the source. A tentative detection on May 15 by BIMA was reported by Smith and Gruendl (1997), but was not confirmed by a deeper analysis of the data (Gruendl et al. 1997). Optical observations were selected with emphasis on days 5-25 after the burst, calibrating $m_R = 0$ as 3080 Jy (Bessell 1979).

Fluxes at centimetre wavelengths are at 8.46 GHz from the VLA by Frail et al. (1997b) and 8.41 GHz from VLBI by Taylor et al. (1997). The VLA has observed GRB 970508 at 4.86 GHz and 1.43 GHz, too, but less frequently, which is the reason why only the 8.46 GHz data are plotted here.

Pooley and Green (1997) detected the source at the MRAO on May 16.5 ($F_{15\,\rm GHz} = 1.57 \pm 0.25$ mJy) and on May 17-22 ($F_{15\,\rm GHz} = 0.66 \pm 0.11$ mJy). From the available fluxes from VLA, VLBI, MRAO and IRAM, one can derive a finer record of the spectral development than previously possible.

The time dependence of the γ, x-ray and optical fluxes of GRB 970508 agrees with a power law fading for a given band of the form $F \propto t^{-1.1 \pm 0.1}$ which was at least once interrupted by a flare (Piro et al. 1997b).

Compared to this, the radio data at 8.46 and 4.84 GHz (Frail et al. 1997b) show approximately constant average fluxes, with many superimposed flares that occur independently at the two frequencies. About 30 days after the burst, these flares calm down, and the fluxes vary in a more similar way. The variations could be either extrinsic or intrinsic to the source: In the first case, one assumes a constant source-intrinsic flux that is modified by interstellar scintillation (IS) in our galaxy. As the source expands, the scintillation characteristics pass from the strong diffractive to the weak refractive regime (Goodman 1997, Frail et al. 1997b). The intrinsic case demands shock induced coherent/collective plasma emission as in intra-day variable QSO's (see e.g. Standke et al. 1996). Both effects can produce strong narrow-band variations in the cm range while not influencing the optical light curve.

We will now discuss how the mm observations reported here fit in this context. They are not consistent with a constant flux, because the fading after May 22 is highly significant (the non-detection on May 28 has nearly the same r.m.s. as the 6.5σ detection on May 17-22). Also, they do not fit well the high energy power law above.

An important point to be verified is the possibility of external flux modification, i.e. if an intrinsically weak, constant mm source could have been boosted on three occasions above the detection limit by IS. We argue that this is highly improbable, as flux modulations close to 100% can only be produced by strong diffractive IS, whose maximum frequency ν_c at the GRB's galactic latitude of $b \approx 27^\circ$ reaches ≈ 17.3 GHz for typical galactic scattering measures (Goodman 1997). The weak refractive type of IS has no such limiting frequency, but the

Table 1. Overview of decimal UT dates, frequencies, fluxes, offsets, beams (major axis, minor axes, PA), applied decorrelation factors from UV plane point source fits, configurations and weather conditions during the PdBI observations of GRB 970508. Fluxes are the maxima of UV plane point source fits with 1σ map r.m.s. Calibrators: (1) 3C273 $F_{87.7\,\mathrm{GHz}} = 32.9$ Jy, (2) MWC349 $F_{86.2\,\mathrm{GHz}} = 0.95$ Jy, (3) 3C454.3 $F_{87.7\,\mathrm{GHz}} = 5.5$ Jy, (4) 2200+420 $F_{86.2\,\mathrm{GHz}} = 3.7$ Jy, (5) NRAO530 $F_{86.2\,\mathrm{GHz}} = 5.2$ Jy, (6) 0923+392 $F_{87.7\,\mathrm{GHz}} = 5.9$ Jy (from Dutrey and Ungerechts 1997)

UT start – end	ν [GHz]	flux [mJy]	$\Delta\alpha, \Delta\delta$ (″,″)	Beam(″,″,°)	f_{decorr}	config.	weather	calibrators
May 17.35 – 17.49	86.20	(0.45 ± 0.80)	$0.0, 0.0$	$5.3, 2.6, 101$	0.93	5C2	cloudy	(3)
May 18.98 – 19.16	86.24	2.38 ± 0.51	$-0.9, -1.4$	$7.0, 2.7, 13$	0.93	5C2	clear	(4), (2)
May 21.09 – 21.20	86.20	1.74 ± 0.43	$-1.0, +0.9$	$7.0, 2.7, -2$	0.97	5C2	clear	(5), (2)
May 22.89 – 23.09	87.76	1.64 ± 0.47	$-0.4, +0.9$	$5.4, 2.9, 42$	0.92	5C2	cloudy	(1), (2)
May 23.20 – 23.55	87.76	(0.38 ± 0.61)	$0.0, 0.0$	$3.9, 3.1, -43$	0.74	5C2	cloudy	(3)
May 28.23 – 28.59	86.00	(-0.01 ± 0.29)	$0.0, 0.0$	$3.6, 3.1, 75$	0.89	5C2	clear	(1), (6)
Aug 12.89 – 13.18	86.55	(0.14 ± 0.38)	$0.0, 0.0$	$11.5, 7.5, -36$	0.97	5D-N09	clear	(5), (2)
May 18.98 – 19.16	232.03	(1.62 ± 2.27)	$0.0, 0.0$	$2.3, 1.0, 19$	0.74	5C2	clear	(4), (2)
May 21.09 – 21.20	232.03	(-3.05 ± 2.11)	$0.0, 0.0$	$2.3, 1.0, -5$	0.84	5C2	clear	(5), (2)
May 22.89 – 23.09	228.40	(0.67 ± 3.00)	$0.0, 0.0$	$2.0, 1.1, 33$	0.60	5C2	cloudy	(1)

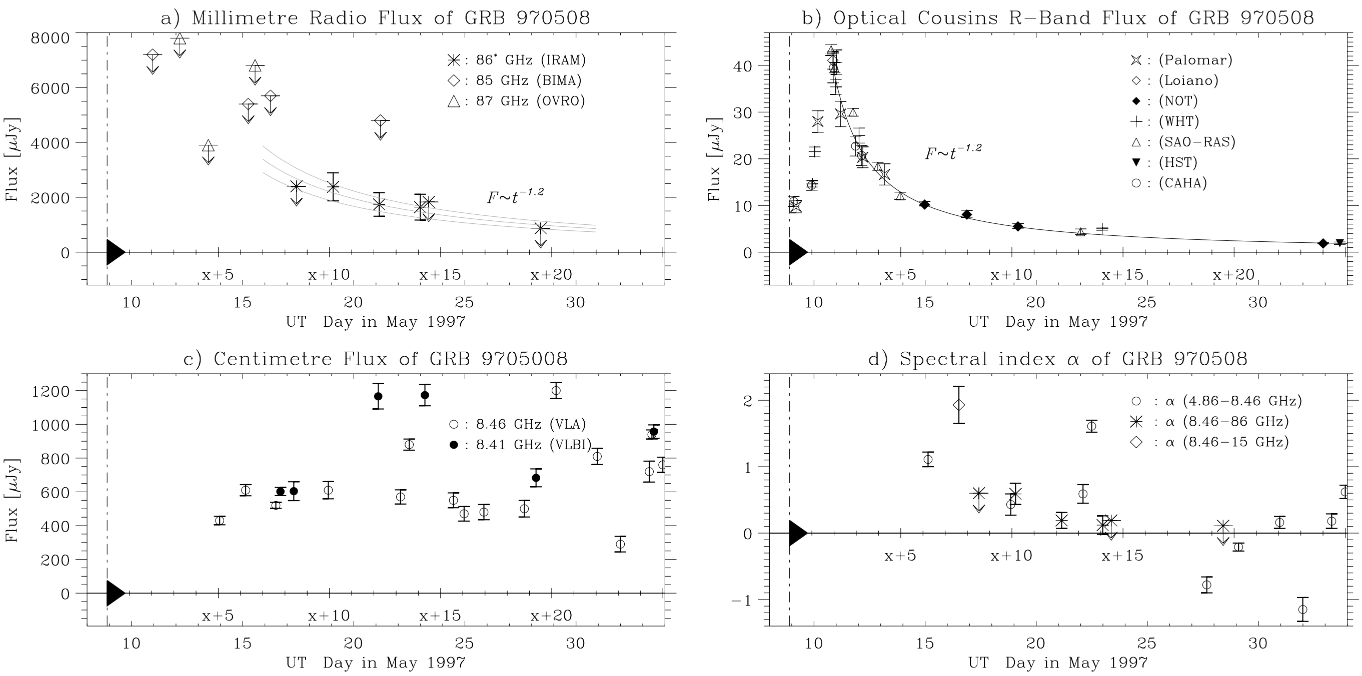

Fig. 1a–d Evolution of the flux of GRB 970508 in the **a** millimetre, **b** optical and **c** centimetre range, and **d** of the spectral index α. References are: IRAM (this article, Table 1), BIMA: Gruendl et al. (1997), OVRO: Shepherd et al. (1997), Palomar: Djorgovski et al. (1997), Loiano: Mignoli et al. (1997), NOT: Pedersen et al. (1998), WHT: Galama et al. (1997b), SAO-RAS: Sokolov et al. (1997), HST: Fruchter et al. (1997), VLA: Frail et al. (1997b), VLBI: Taylor et al. (1997), CAHA: Castro-Tirado et al. (1998). Spectral indices: $\alpha_{4.86-8.46\,\mathrm{GHz}}$ from Frail et al. (1997b), others from Table 2. Optical data are corrected with $A_r = 0.07$ (Djorgovski et al. 1997). Palomar and Loiano Gunn-r data were converted to Cousins R with Fukugita et al. (1995)

r.m.s. of its amplitude modulation scales with ν^{-2}, so that any variation at 8.46 GHz is reduced by a factor of ≈ 0.01. Also, for $\nu > \nu_c$, timescales for weak diffractive and refractive IS scale with the Fresnel length $r_f \propto \nu^{-0.5}$ (Goodman 1997) which would be some hours at 86.2 GHz. No significant flux variation has been seen on this timescale (Sect. 2).

For the intrinsic light curves of GRB 970508, two mechanisms seem to dominate: self-similar forms with power-law fading, which pass in time from high to low energies (interpreted as non-thermal emission from a decelerating relativistic fireball, e.g. Vietri 1997, Waxman 1997, Wijers et al. 1997), and closely correlated broad-band flares (Piro et al. 1997b). Fig. 1a,b show that optical flares were absent during our mm detections. Near 8.4 GHz (Fig 1c), the situation on May 21-23 is less clear, as flares from intrinsic and extrinsic origins could be present in the cm records. The closest fluctuation at 8.4 GHz is a strongly double-peaked feature, which is difficult to associate with the constant mm flux levels during the May 21,22

Table 2. Spectral index α from observations which closely match in time. Data are from: (1) this article, (2) Frail et al. (1997b), (3) Taylor et al. (1997), (4) Pooley and Green (1997). Columns are UT day in May, frequency, flux and reference for both observations, the mean UT day, and the spectral index $\alpha = log_{10}(F_{\nu 1}/F_{\nu 2})/log_{10}(\nu_1/\nu_2)$ assuming a power law $F \propto \nu^{\alpha}$ between frequency pairs

UT_1	ν_1 [GHz]	$F_{\nu 1}$ [μJy]	Ref_1	UT_2	ν_2 [GHz]	$F_{\nu 2}$ [μJy]	Ref_2	UT_{mean}	α
16.52	15.0	1570 ± 250	(4)	16.49	8.46	520 ± 18	(2)	16.51	1.93 ± 0.29
17.42	86.2	< 2400	(1)	17.3	8.41	604 ± 56	(3)	17.36	< 0.6
19.07	86.24	2380 ± 510	(1)	18.85	8.46	610 ± 51	(2)	18.96	0.59 ± 0.16
21.14	86.2	1800 ± 440	(1)	21.1	8.41	1166 ± 75	(3)	21.12	0.19 ± 0.12
22.99	87.76	1640 ± 447	(1)	23.2	8.41	1175 ± 63	(3)	23.1	0.12 ± 0.14
23.38	86.76	< 1830	(1)	23.2	8.41	1175 ± 63	(3)	23.1	< 0.19
28.41	86.0	< 870	(1)	28.2	8.41	683 ± 53	(3)	28.3	< 0.11

detections. For our May 19 observation, the closest VLA observation from May 18.85 shows a quiescent source at 8.46 GHz. This makes broad-band flaring an unlikely mechanism for the millimetre light curve.

A power-law fading form would require to place the time of maximum 86.2 GHz flux between the optical maximum ($\approx$ May 11) and an 8.4 GHz peak (e.g. the May 21-23 flare). For this, the May 17 upper limit must receive a low weight, and one would have expected a "barely missed" detection on May 28 from the $F \propto t^{-1.1 \pm 0.1}$ law, which is not the case (Table 1). Such a fading cannot be ruled out, but it is not a good fit (Fig. 1a).

4. Conclusions

The PdBI observations of GRB 970508 gave a significant detection at 86.2 GHz and a non-detection at 232 GHz. Studying the frequency dependencies of interstellar scintillation, we find that the 86.2 GHz fluxes are very likely intrinsic to the source. With high significance, the source has passed from detection to non-detection in the millimetre range between days 14 to 19 after the burst, without showing correlated flares in the optical or cm range.

The light curve at 86.2 GHz is not well fitted by the power law decline $F \propto t^{-1.1 \pm 0.1}$ seen at higher frequencies, although it is not excluded. A better match would be the form "fast rise - nearly constant level - fast decline".

We conclude that mm observations provide an new aspect of the spectral development of GRB's, allowing to probe the interior of the relativistic shock fronts with a low risk of distortion by interstellar scintillation.

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References

Ali S. et al. 1997, ApJ **487**, 114
Bessell M.S. 1979, PASP **91**, 543
Boella G. et al. 1997, A&AS **122**, 299
Bond E.H. 1997, IAUC 6654
Castro-Tirado A.J. et al. 1998, Science, in press
Costa E. et al. 1997a, IAUC 6576
Costa E. et al. 1997b, IAUC 6649
Djorgovski S.G., et al. 1997, Nature **387**, 876
Dutrey A., Ungerechts H. 1997, IRAM Flux Rep. **15**
Fishman G.J., Meegan C.A. 1995, ARA&A **33**, 415
Frail D.A. et al. 1997a, IAUC 6662
Frail D.A. et al. 1997b, Nature **389**, 261
Frontera F. et al. 1997, A&AS **122**, 357
Fruchter A. et al. 1997, IAUC 6674
Fukugita M. et al. 1995, PASP **107**, 945
Galama T.J. et al. 1997a, Nature **387**, 479
Galama T.J. 1997b, preprint, priv. comm.
Goodman J. 1997, astro/ph-9706084
Gruendl R.A. et al. 1997, Proc. 4^{th} Huntsville GRB Symp., in press
Guilloteau S. et al. 1992, A&A **262**, 624
Hudec R. 1995, Ap&SS **231**, 239
Jager R. et al. 1997, A&AS **125**, 557
Klebesadel R.W., Strong I.B., Olson R.A. 1973, ApJ **182**, L85
Metzger M.R. et al. 1997a, IAUC 6672
Metzger M.R. et al. 1997b, Nature **287**, 878
Mignoli M. et al. 1997, IAUC 6661
Park H.S. et al. 1997, ApJ **490**, L21
Pedersen H. et al. 1998, ApJ **496**, in press
Piro L. et al. 1997, IAUC 6656
Piro L. et al. 1997b, astro-ph/9710355
Pooley G., Green D. 1997, IAUC 6670
Quirrenbach A. et al. 1991, ApJ **372**, L71
Sahu K.C. et al. 1997, Nature **387**, 476
Shepherd, D.S. et al. 1997, IAUC 6664
Smith I.A., Gruendl R.A. 1997, IAUC 6663
Sokolov V.V. et al. 1997, astro-ph/9709093
Standke K.J. et al. 1996, A&A **306**, 27
Taylor G.B. et al. 1997, Nature **389**, 263
Van Paradijs J. et al. 1997, Nature **386**, 686
Vietri M. 1997, ApJ **488**, L105
Vrba F.J. et al. 1997, ApJ **446**, 115
Wagner S.J. et al. 1996, Astron. J. **111**, 2187
Waxman E. 1997, ApJ **489**, L313
Wijers R.A.M.J. et al. 1997, MNRAS **288**, L51