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The 1.4 GHz light curve of GRB 970508

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ABSTRACT

We report on Westerbork 1.4 GHz radio observations of the radio counterpart to γ-ray burst GRB 970508, between 0.80 and 138 days after this event. The 1.4 GHz light curve shows a transition from optically thick to thin emission between 39 and 54 days after the event. We derive the slope p of the spectrum of injected electrons ($\mathrm{d}N/\mathrm{d}\gamma_\mathrm{e} \propto \gamma_\mathrm{e}^{-p}$) in two independent ways which yield values very close to $p = 2.2$. This is in agreement with a relativistic dynamically near-adiabatic blast wave model whose emission is dominated by synchrotron radiation and in which a significant fraction of the electrons cool fast.

Subject headings: gamma rays: bursts — gamma rays: individual (GRB 970508) — radio continuum: general

1. Introduction

The peak luminosities of γ-ray bursts (GRBs) are highly super-Eddington and require relativistic outflows (Paczyński 1986; Goodman 1986). Paczyński and Rhoads (1993) pointed out that radio emission is expected as a result of the interaction between such

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a relativistic outflow and an external medium, as is, e.g., observed in extragalactic jet sources (see also Katz 1994; Mészáros and Rees 1997). They estimated that the strongest GRBs may be followed by transient ($\sim$ 10 mJy) radio emission at intervals ranging from minutes (for a distance $d \sim 10^5$ pc) to several weeks ($d \sim 10^9$ pc). However, searches for radio counterparts through follow-up observations (Frail et al. 1994,1997a; Koranyi et al. 1995; Galama et al. 1997a,b) were without success until recently. With the rapid accurate location capability of the Wide Field Cameras (WFCs; Jager et al. 1995) onboard the Italian-Dutch X-ray observatory BeppoSAX (Piro et al. 1995) it has recently become possible to detect fading X-ray, optical and radio counterparts to GRBs (Costa et al. 1997a; Piro et al. 1997a; Groot et al. 1997a,b; Van Paradijs et al. 1997; Galama et al. 1997c,1998a; Sahu et al. 1997; Bond 1997; Metzger et al. 1997; Frail et al. 1997b,c; Bremer et al. 1998; Halpern et al. 1997). These observations have settled the discussion on the GRB distance scale ('galactic halo' versus 'cosmological', see e.g. Fishman and Meegan 1995, Lamb 1995, Paczyński 1995): GRBs occur at Gpc distances.

GRB 970508 is the first GRB to be detected in the radio (Frail et al. 1997b,c); the radio source position coincides with that of the optical (Bond 1997) and X-ray (Piro et al. 1997b) afterglow sources. Assuming that the variations of the source at 4.86 and 8.46 GHz are due to interstellar scintillation (ISS), their damping with time is consistent with a highly relativistically expanding shell passing a diameter of $\approx 3\mu$as (Frail et al. 1997b). VLBI observations show that the source is unresolved ($<$ 0.3 mas, Taylor et al. 1997).

We here report on the results of 1.4 GHz radio observations of GRB 970508, made with the Westerbork Synthesis Radio Telescope (WSRT) between 0.80 and 138 days after the burst occurred.

2. Radio Observations

On May 8.904 UT BeppoSAX recorded a moderately bright GRB (Costa et al. 1997b) with the Gamma-Ray Burst Monitor (GRBM; Frontera et al. 1991), which was also recorded with the Wide Field Cameras on board BeppoSAX. Analysis of the WFC observations gave a $3'$ (3σ radius) error box centered on RA= $06^{\rm h}53^{\rm m}28^{\rm s}$, Dec = $+79^\circ17'\!.4$ (J2000; Heise et al. 1997b). The burst was also recorded (Kouveliotou et al. 1997) with the Burst and Transient Source Experiment (BATSE; Fishman et al. 1989) on board the Compton Gamma-Ray Observatory.

The error box of GRB 970508 was first observed at 1.4 GHz with the WSRT at the preliminary position given by Heise et al. (1997) on May 9.70 UT, starting 0.80 days after the event, for 9.0 hours. We used the standard WSRT 1.4 GHz receiving system and continuum correlator, providing us with 5 bands of width 10 MHz and 3 bands of width 5 MHz. The noise level in a continuum map after 12 hours of integration is typically 0.05 mJy beam^{-1} for 14 telescopes and the full 65 MHz bandwidth. For the declination of GRB 970508, at 1.4 GHz, the synthesized beamwidth is $13'' \times 13''$ (full width at half maximum; FWHM), and the field of view is about $0\overset{\circ}{.}6$. Table 1 provides a log of the observations.

The data were analyzed using the NEWSTAR software package[9]. The interferometer complex visibilities were first examined for possible electromagnetic interference and other obvious defects. Bands with strong interference were either deleted or carefully edited. Interference was usually limited to about 5 % of the data. The interferometer gain and phase, for each observation and each band, were calibrated using the standard WSRT calibrators 3C 48, 3C 147 and 3C 286 (15.96, 9.50 and 14.77 Jy, respectively at 1.4 GHz; Baars et al. 1977). We constructed a model of the GRB 970508 field (used for deconvolution) that contains 95 point sources and 60 clean components, (together about 100 sources) and is complete down to a level of $\sim$ 0.45 mJy. No self calibration was performed.

2.1. The light curve

Due to noise the location of a source in the radio map can shift by roughly 0.5 FWHM/SNR, where SNR is the signal-to-noise ratio of the detection. For very low SNR detections the shift can be fairly large. If we would take a peak in the map near the location of GRB 970508 we would bias ourselves systematically to higher flux densities (as we cannot discern whether the peak is due to noise on top of the detection or the detection itself). Therefore, we constructed the light curve using the flux density at the pixel on the exact position of the radio counterpart (Frail 1997c). The errors (1σ) are the r.m.s. map noises (determined by a quadratic fit to the deconvolved image). The maps are super sampled with $\sim$ 6 pixels beam^{-1}. Negative flux density values in the 1.4 GHz light curve are due to r.m.s. noise fluctuations on a non- or weakly-detectable source. The 1.4 GHz light curve is shown in Fig. 1. We also divided the data from May 9 until September 23 into 8 parts and added the observations in each part to determine average flux densities. In Table 2 and in Fig. 1 we present these average flux densities.

During the first 40 days after the onset of GRB 970508 the 1.4 GHz radio counterpart is not detected. A combined map of all observations (May 9.7-June 16.44 UT; excluding June 8.43 UT for reasons of data quality) yields 33 $\pm$ 40 μJy. The average 4.86 GHz

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[9]http://www.nfra.nl:80/newstar/

flux density during the first 50 days is 560 ± 10 μJy (Frail et al. 1997b), implying that, on average, the spectral index $\alpha_{1.4-4.86\mathrm{GHz}} > 1.5$ (where we used a 2σ upper limit of 80 μJy at 1.4 GHz), i.e. the radiation is self-absorbed ($F_\nu \propto \nu^2$; Katz and Piran 1997). At later times ($t > 50$ days) 1.4 GHz emission is detected at, on average, 228 ± 30 μJy (Jul 1.49–Sep 23.22; 53.6-138.3 days after the event). From Tab. 2 we see that then the spectral indices $\alpha_{1.4-4.86\mathrm{GHz}}$ and $\alpha_{1.4-8.46\mathrm{GHz}}$ are consistent with the expected low frequency tail of synchroton radiation ($F_\nu \propto \nu^{1/3}$; Rybicky and Lightman 1979). Hence a transition from optically thick to thin emission occurred between 39 and 54 days after the event (see also Frail et al. 1997b).

During the first month the 8.46 and 4.86 GHz flux densities show rapid fluctuations, attributed to ISS, with an ISS diffractive time scale t_{dif} of less than a day, and decorrelation bandwidth ν_{dec} of less than 2 GHz (Frail et al. 1997b). For 1.4 GHz this implies $t_{\mathrm{dif}} \sim$ 3 hours and $\nu_{\mathrm{dec}} \sim 0.8$ MHz (Goodman 1997). Hence ISS is not likely to affect the 1.4 GHz light curve: it was constructed from observations with long integration times (> 3 hrs) and the full bandwidth (65 MHz). At 1.4 GHz the critical angular size below which diffractive scintillation can be observed is a factor 4.5 smaller than at 4.86 GHz (Goodman 1997). Assuming that the apparent expansion velocity of the blast wave is constant and using the fact that Frail et al. (1997b) observed scintillation at 4.86 GHz until day ~ 30 we would expect diffractive ISS to modulate the 1.4 GHz flux density for $t < 7$ days. We have searched for diffractive ISS in the individual 5 and 10 MHz bands during the first two weeks, dividing the data into segments of 6 hours (a trade off between the ISS decorrelation time and a sufficient amount of data). We find only one $> 3\sigma$ detection (550 ± 160 μJy; 3.4 σ) on May 11.51 at 1.415 MHz (10 MHz bandwidth). The probability of a 3.4 σ detection in ~ 100 independent measurements (with an asumed Gaussian distribution) is ~ 3 %. We conclude that ISS was not observed by us at 1.4 GHz.

3. Discussion

The observed optical spectral slope α and the optical power law decay of the light curve $F_\nu \propto t^\delta$ is not consistent with the expected relation for the simplest blast wave model ($\delta = 3\alpha/2$; e.g. Wijers, Rees and Mészáros 1997). The observed power law decay value, $\delta = -1.141 \pm 0.014$ ($t > 2$ days, Galama et al. 1998b; see also Pedersen et al. 1998, Castro-Tirado et al. 1998, Sokolov et al. 1998) would imply $\alpha = -0.761 \pm 0.009$, while in the optical passband $\alpha = -1.12 \pm 0.04$ is observed (Galama et al. 1998c, from here on Paper II; see also Sokolov et al. 1998). In the following we show that this may be explained by rapid cooling of a significant fraction of the electrons.

A population of electrons with a power-law distribution of Lorentz factors $\gamma_{\rm e}$ ($dN/d\gamma_{\rm e} \propto \gamma_{\rm e}^{-p}$) above some minimum value $\gamma_{\rm m}$ emits a power law synchrotron spectrum above the frequency $\nu_{\rm m}$ (corresponding to radiating electrons with $\gamma_{\rm m}$; e.g. Rybicki & Lightman 1979). Independently, above some Lorentz factor $\gamma_{\rm c}$ the electrons may cool rapidly, and an extra break in the spectrum is expected at the corresponding frequency $\nu_{\rm c}$ (Sari, Piran, & Narayan 1998). Beyond a certain time t_0 (t_0 is small $\sim$ 500 sec; see Paper II) the evolution of the blast wave is adiabatic (Sari et al. 1998 and see Paper II); then $\nu_{\rm m} < \nu_{\rm c}$, and the spectrum varies as $F_\nu \propto \nu^{-(p-1)/2}$ from $\nu_{\rm m}$ up to $\nu_{\rm c}$; above $\nu_{\rm c}$ it follows $F_\nu \propto \nu^{-p/2}$ and below $\nu_{\rm m}$ it follows the low frequency tail, $F_\nu \propto \nu^{1/3}$ (Sari et al. 1998). The evolution in time of the GRB afterglow is determined by the evolution of these break frequencies: $\nu_{\rm c} \propto t^{-1/2}$ and $\nu_{\rm m} \propto t^{-3/2}$ (both decrease with time).

The decay part of the optical $R_{\rm c}$ (Coussins R) band light curve (in the optical passband $\nu > \nu_{\rm c}$ for $t \gtrsim 1.2$ days; Paper II) goes as $F_\nu \propto t^{(2-3p)/4}$, while the spectrum is then $F_\nu \propto \nu^{-p/2}$ (Sari et al. 1998). This allows us to make two independent measurements of p: using $F_{R_{\rm c}} \propto t^{-1.141\pm0.014}$ we find $p = 2.188 \pm 0.019$ and using $\alpha_{\rm opt} = -1.12 \pm 0.04$ gives $p = 2.24 \pm 0.08$. The excellent agreement between the values of p supports that a significant fraction of the electrons cool rapidly and that the evolution of the GRB remnant is adiabatic. Additional evidence for rapid cooling of a significant fraction of the electrons is given in Paper II.

Observations by Bremer et al. (1998) with the IRAM Plateau de Bure Interferometer (PdBI) at 86 GHz show a maximum around $\sim$ 12 days. We identify this maximum with the break frequency $\nu_{\rm m}$ passing 86 GHz at $t_{\rm m,86GHz} \sim 12$ days (Paper II). We expect, the 8.46 and 1.4 GHz emission to peak at $t_{\rm m,8.46GHz} \sim 55$ days and $t_{\rm m,1.4GHz} \sim 180$ days, respectively ($\nu_{\rm m} \propto t^{-3/2}$). Near day 55, a shallow maximum can be seen in the 8.46 GHz light curve (Frail et al. 1997b). Unfortunately our 1.4 GHz light curve cannot be used to test the presence of the maximum at that frequency, both due to low signal to noise and because it ends 150 days after the burst, i.e. before the predicted maximum.

Before $\nu_{\rm m}$ passes 8.46 GHz at $t_{\rm m,8.46GHz}$ we expect the 8.46 GHz spectrum to follow the low frequency tail $F_\nu \propto \nu^{1/3}$, while after $t_{\rm m,8.46GHz}$ it is expected to be $F_\nu \propto \nu^{-(p-1)/2} = \nu^{-0.6}$ (Sari et al. 1998 and we have used $p = 2.2$). Thus, we predict a gradual transition between $t_{\rm m,8.46GHz} \sim 55$ days and $t_{\rm m,4.86GHz} \sim 80$ days (when also at 4.86 GHz $\nu_{\rm m}$ has passed) from $\alpha = 1/3$ to $\alpha = -0.6$. We note that this expectation is different from blast wave models that do not include the effect of rapid cooling of a significant fraction of the electrons ($F_\nu \propto \nu^{-1.1}$ similar to the optical slope; see e.g. Wijers et al. 1997). Also the decays at 8.46 GHz (after $t_{\rm m,8.46GHz} \sim 55$ days) and 4.86 GHz (after $t_{\rm m,4.86GHz} \sim 80$ days) are expected to be different from that in the optical and X-ray passbands, $F_\nu \propto t^{3(1-p)/4} = t^{-0.9}$; where we have used p

= 2.2). These predictions can be tested with the continued monitoring at the VLA at 4.86 and 8.46 GHz by Frail et al. (1998).

The radio afterglow light curves of GRB 970508 (Frail et al. 1997b and this Letter) show a much more gradual evolution than expected (see e.g. the fit to the 8.46 and 4.86 GHz data by Waxman, Kulkarni and Frail 1998). Also a constant self-absorption frequency was expected (e.g. Waxman et al. 1997) while we here show that a transition from optically thick to thin emission occurred around $\sim$ 45 days. For $t < t_o$ Sari et al. (1998) predict a decrease with time of the self-absorption frequency, $\nu_{\rm a}$, while for $t > t_0$ the self-aborption frequency $\nu_{\rm a}$ remains constant. The transition from optically thick to thin 1.4 GHz radiation then suggests that $t_0 \sim 45$ days. Also the 8.46 GHz light curve (Frail et al. 1997b) suggests that t_0 cannot be much smaller than 10 days, i.e. 10 days $\lesssim t_0 \lesssim 55$ days (we have extrapolated backwards in time from the 8.46 GHz peak at $t_{\rm m} \sim 55$ days with the expected dependence $F_\nu \propto t^{1/2}$ for times $t < t_{\rm m}$). This is not in agreement with the finding that $t_0 \sim 500$ sec (Paper II). However, the absence of a break in the smooth power law decay of the optical light curve from 2 to 60 days after the burst (Pedersen et al. 1998; Castro-Tirado et al. 1998; Sokolov et al. 1998; Galama et al. 1998c) shows that there is no important transition in that period. This does imply that some additional ingredient is needed; for example, Waxman et al. (1998) argue that the transition from ultrarelativistic to mildly relativistic expansion of the blast wave may explain the decrease in the self-absorption frequency $\nu_{\rm a}$ with time and the slow time dependence of the early radio light curves.

The excellent agreement in the derived value for p (p = 2.2) from the decay of the optical light curve and the optical spectral slope support an adiabatic dynamical evolution of the GRB remnant and an extra break in the synchrotron spectrum at the frequency $\nu_{\rm c}$ above which the radiation is from electrons which cool rapidly compared to the remnant's expansion time. We predict a transition in the radio spectral index $\alpha_{4.86-8.46\rm GHz}$ from 1/3 to –0.6, between 55 and 80 days; the light curves are predicted to decay as $F_\nu \propto t^{-0.9}$ after 55 days at 8.46 GHz and 80 days at 4.86 GHz.

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Table 1: 1.4 GHz WSRT observations.

UT day (1997)[a]	Δt (days)	Length (hrs)	$F_{1.4\rm GHz}$ (mJy)	UT day (1997)[a]	Δt (days)	Length (hrs)	$F_{1.4\rm GHz}$ (mJy)
May 9.70	0.80	9.0	–0.09 ± 0.08	Jun 14.37	36.47	3.9	0.07 ± 0.12
May 10.64	1.73	12.0	0.02 ± 0.07	Jun 15.37	37.47	4.1	0.01 ± 0.12
May 11.63	2.73	12.0	0.14 ± 0.07	Jun 16.44	38.54	7.4	0.09 ± 0.13
May 14.62	5.72	12.0	–0.07 ± 0.08	Jul 1.49	53.59	12.0	0.37 ± 0.05
May 16.63	7.73	12.0	0.18 ± 0.08	Jul 14.45	66.55	7.7	0.49 ± 0.08
May 18.61	9.71	12.0	–0.06 ± 0.07	Jul 26.62	78.71	2.8	0.11 ± 0.14
May 20.82	11.92	7.4	–0.03 ± 0.11	Aug 4.23	87.33	4.1	0.43 ± 0.17
May 21.61	12.70	12.0	–0.08 ± 0.08	Aug 14.20	97.29	3.6	0.22 ± 0.21
May 23.43	14.53	3.9	–0.29 ± 0.13	Aug 16.25	99.35	6.5	0.14 ± 0.10
May 25.77	16.87	3.3	0.11 ± 0.16	Aug 17.28	100.38	8.0	0.17 ± 0.08
May 27.73	18.83	5.3	0.20 ± 0.11	Aug 18.23	101.33	5.6	0.08 ± 0.10
May 30.39	21.49	3.0	0.07 ± 0.13	Aug 20.30	103.40	5.6	0.25 ± 0.08
May 31.40	22.50	3.4	0.13 ± 0.12	Aug 22.23	105.33	6.1	0.20 ± 0.09
Jun 1.39	23.48	2.9	0.06 ± 0.14	Aug 29.17	112.27	4.3	0.48 ± 0.12
Jun 2.39	24.49	3.4	0.10 ± 0.12	Sep 1.17	115.27	4.6	0.08± 0.10
Jun 6.42	28.52	5.3	0.07 ± 0.15	Sep 9.22	123.32	6.6	0.36 ± 0.09
Jun 8.43	30.52	5.9	0.03 ± 0.37	Sep 23.22	138.32	10.2	0.26 ± 0.10
Jun 10.7	32.81	4.1	0.05 ± 0.14				

[a]Observing times refer to the middle of the observing period

Table 2: 1.4, 4.86 and 8.46 GHz long-term averages and 1.4 GHz spectral indices (with respect to 8.46 and 4.86 GHz). The 8.46 and 4.86 GHz averages have been determined from observations by Frail et al. (1997b).

UT day (1997)	$F_{1.4\,\rm GHz}$	$F_{4.86\,\rm GHz}$	$F_{8.46\,\rm GHz}$	$\alpha_{1.4-4.86\rm GHz}$	$\alpha_{1.4-8.46\rm GHz}$
May 9.70 - May 16.63	35 ± 40	330 ± 33	531 ± 12	> 1.05	> 1.04
May 18.61- May 25.77	–70 ± 55	390 ± 25	669 ± 17	> 0.96	> 0.99
May 27.73-Jun 2.39	110 ± 70	728 ± 20	810 ± 14	> 1.30	> 0.97
Jun 6.42-Jun 16.44[a]	55 ± 65	655 ± 21	612 ± 33	> 1.27	> 0.83
Jul 1.49 - Aug 4.23	306 ± 65	558 ± 13	594 ± 14	0.48 ± 0.17	0.37 ± 0.12

[a]Excluding June 8.43 UT

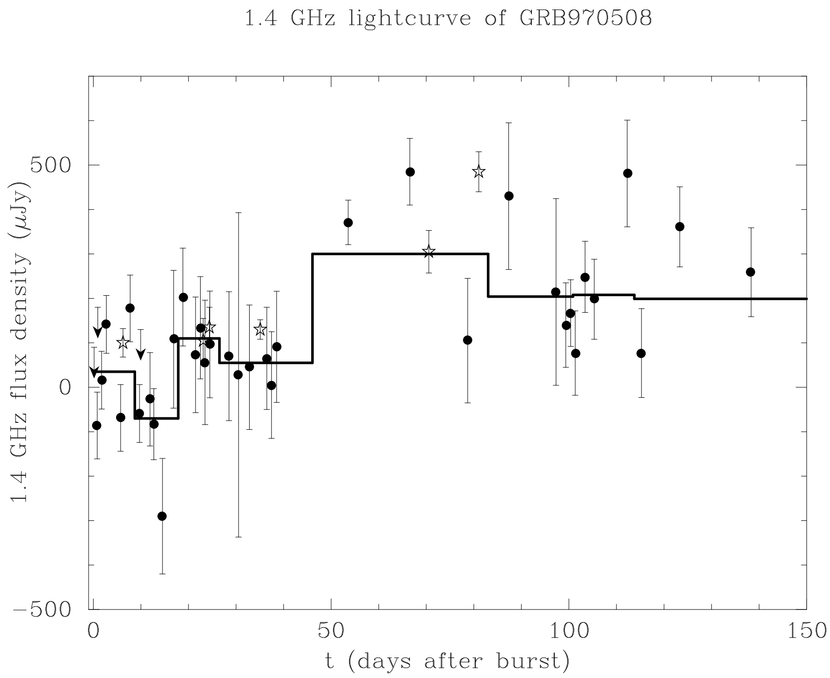

Fig. 1.— The 1.4 GHz light curve of GRB 970508. The data are from Tab. 1 (•) and Frail et al. (1997b; $\star$ and the 2σ upper limits). The histogram represents long-term average WSRT 1.4 GHz flux densities from Tab. 2.