The radio afterglow from the γ-ray burst of 8 May 1997

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Important insight into the nature of γ-ray bursts (GRBs) has been gained in recent months mainly due to the immediate, precise localization of the bursts[1–3] and the discovery of relatively long-lived X-ray afterglows[1,4] by the satellite BeppoSAX[5]. These advances have enabled deep searches which have led to the discovery of optical transients[6,7] coincident with fading X-ray sources. Optical spectroscopy of the latest burst (GRB970508; ref. 8) has clearly demonstrated that it lies at a cosmological distance, thus resolving a long-standing controversy about the distance scale to GRBs. Here we report a variable radio source within the error box of GRB970508 and coincident with the optical transient. We suggest that this is the much-sought-after radio counterpart of a GRB. If the observed fluctuations in the radio emission ('twinkling') are a result of a strong scattering by the irregularities in the ionized Galactic interstellar gas, then the source must have an angular size of about 3 microarcseconds in the first few weeks. The damping of the fluctuations with time indicates that the source expands to a significantly larger size later on.

Radio observations began at the Very Large Array (VLA) at 1997 May 9.06 UT, only 3.7 h after the γ-ray burst[2]. This and the next observation (May 9.84 UT) were conducted in the 1.43-GHz band. No radio sources were found in the preliminary 5-arcmin error circle, with 2σ limits of 0.09 and 0.18 mJy, respectively. On 1997 May 10 UT the position of the GRB was refined[3] to a circle of radius 3 arcmin. At about the same time, an optical variable was reported[7]. This source lies within the 50-arcsec (radius) localization circle of a transient X-ray source, 1SAX J0653.8 + 7916 (ref. 4). The refined position of the burst enabled us to start observing at higher radio frequencies, specifically 4.86 and 8.46 GHz, for which the fields of view are correspondingly smaller. The first 8.46-GHz observations (1997 May 13.96 UT) resulted in the detection of a single source (flux density $S = 0.43 \pm 0.03$ mJy) within the 3-arcmin GRB error circle and coincident with the optical variable[7,9]; we refer to this source as VLA J065349.4 + 791619.

Our monitoring programme showed that VLA J065349.4 + 791619 is quite variable; the observations are summarized in Table 1 and Fig. 1. The source is unresolved at our highest angular resolution of 0.8 arcsec; the fraction of linear polarization is <9%. The probability of detecting a background radio source at this level in the 50-arcsec-radius error circle by chance is 0.02, small but not insignificant[10]. However, the high degree of radio variability and the unusual radio spectrum (see below and Table 1) make this object interesting. Regardless of these considerations we note that the radio source coincides, within the experimental errors, with the optical variable[9] which is now widely regarded as the optical afterglow of GRB970508. Thus we conclude that VLA J065349.4 + 791619 is most likely to be a radio source associated with GRB970508. Having accepted this hypothesis we now proceed with the interpretation of the radio observations.

The temporal behaviour of the radio flux density in the several months following the initial burst has not mirrored the simple smooth power-law decay of the optical[9,11]. On the contrary, during the first three weeks the radio light curve at 8.46 GHz (Fig. 1a) is erratic with large (50%) fluctuations. The amplitude of these modulations have since decreased, with ~15% variations seen out to at least post-burst day 55. The same trends are seen at 4.86 GHz (Fig. 1b), although the sampling is not as complete.

Leaving aside these large fluctuations we note that the mean radio flux rises to a constant value, the 'plateau value' of ~600 μJy (similar at both 4.86 and 8.46 GHz), remains steady for about 2 months after which there is a slow fall-off. From Fig. 1a we see that the time to rise to the plateau value is about 3 weeks after the burst at 4.86 GHz but only about 10 d at 8.46 GHz. This trend, a rise time which increases with decreasing frequency, continues to flux measurements at 1.43 GHz (Table 1). At this frequency, during the first months the source is either undetectable or weak, with flux <100 μJy. Subsequently the source slowly rises to a value of 500 μJy towards the end of our monitoring period. This is about equal to the plateau value that we noted at the two higher frequencies.

Given the limited number of frequencies (ν) at which the fluxes are measured we use a simple power-law model for the radio spectrum: flux $S_\nu \propto \nu^\alpha$ where α is the spectral index. We specifically discuss the spectrum around 16–17 May 1997 as a number of different frequency measurements are available at this epoch. From Table 1, we note that the spectral index between 1.43 and 8.46 GHz is ~1. This is confirmed by a detection[12] at 15 GHz ($S_{15} = 1.57 \pm 0.25$ mJy). A turnover in the spectrum is required at higher frequencies in order to explain the apparent non-detections at 86 GHz with the BIMA and OVRO instruments[13,14].

Table 1 Radio observations of GRB970508

Epoch (UT)	Δt (d)	$S(1.43)$ (μJy)	$S(4.86)$ (μJy)	$S(8.46)$ (μJy)	α
1997 May 09.06	0.16	< 90 ± 45			
1997 May 09.84	0.93	< 180 ± 90			
1997 May 13.96	5.06			430 ± 25	
1997 May 15.13	6.23	100 ± 32	330 ± 33	610 ± 33	+1.11 ± 0.11
1997 May 16.49	7.59			520 ± 18	
1997 May 18.85	9.95	< 130 ± 63	480 ± 64	610 ± 51	+0.43 ± 0.16
1997 May 22.10	13.20		410 ± 47	570 ± 42	+0.59 ± 0.14
1997 May 22.49	13.59		360 ± 31	880 ± 33	+1.61 ± 0.09
1997 May 24.48	15.58			550 ± 44	
1997 May 24.96	16.06			470 ± 43	
1997 May 28.85	16.95			480 ± 45	
1997 May 27.67	18.77		770 ± 54	500 ± 49	− 0.78 ± 0.12
1997 May 29.10	20.20		1350 ± 55	1200 ± 47	− 0.21 ± 0.06
1997 May 30.95	22.05		740 ± 46	810 ± 48	+0.16 ± 0.09
1997 May 31.99	23.09	105 ± 50	550 ± 43	290 ± 46	− 1.15 ± 0.18
1997 Jun. 02.29	24.39	135 ± 45	650 ± 44	720 ± 62	+0.18 ± 0.11
1997 Jun. 02.41	24.51			940 ± 27	
1997 Jun. 02.90	25.00		540 ± 46	760 ± 45	+0.62 ± 0.10
1997 Jun. 03.94	26.04		530 ± 51	670 ± 43	+0.42 ± 0.12
1997 Jun. 05.97	28.07		850 ± 36	690 ± 28	− 0.38 ± 0.06
1997 Jun. 09.74	31.84		470 ± 38	530 ± 38	+0.22 ± 0.11
1997 Jun. 12.99	35.09	130 ± 22	640 ± 43	600 ± 39	− 0.12 ± 0.09
1997 Jun. 14.73	36.83		590 ± 69	460 ± 66	− 0.45 ± 0.19
1997 Jun. 17.92	40.02		400 ± 49	560 ± 40	+0.61 ± 0.14
1997 Jun. 18.96	41.06		640 ± 55	630 ± 63	− 0.03 ± 0.13
1997 Jun. 20.86	42.96		550 ± 36	800 ± 32	+0.68 ± 0.08
1997 Jun. 22.93	45.03		425 ± 43	645 ± 38	+0.75 ± 0.12
1997 Jun. 26.63	48.73		610 ± 70	680 ± 46	+0.20 ± 0.13
1997 Jun. 28.68	50.78		500 ± 34	565 ± 36	+0.22 ± 0.09
1997 Jul. 02.36	54.46		805 ± 38	805 ± 43	+0.00 ± 0.07
1997 Jul. 04.59	56.69		605 ± 50	710 ± 49	+0.29 ± 0.11
1997 Jul. 11.10	63.20		630 ± 32	725 ± 40	+0.25 ± 0.07
1997 Jul. 14.61	66.71		585 ± 48	680 ± 46	+0.27 ± 0.11
1997 Jul. 15.33	67.43		550 ± 31	630 ± 37	+0.24 ± 0.08
1997 Jul. 18.44	70.54	305 ± 48	505 ± 62	575 ± 61	+0.23 ± 0.16
1997 Jul. 18.64	70.74		535 ± 43	515 ± 41	−0.07 ± 0.11
1997 Jul. 22.55	74.65		385 ± 51	440 ± 51	+0.24 ± 0.18
1997 Jul. 28.95	81.05	485 ± 45			
1997 Jul. 30.46	82.56		360 ± 70	455 ± 85	+0.42 ± 0.27
1997 Aug. 04.01	87.11		370 ± 38	380 ± 42	+0.05 ± 0.15

Column headings have meanings as follows. 'Epoch' is the start of each observation. 'Δt' is the time elapsed since start of the burst. Columns headed by '$S(1.43)$', '$S(4.86)$' and '$S(8.46)$' contain the radio flux densities and their 1σ errors for VLA J065349.4 + 791619 at 1.43 GHz, 4.86 GHz and 8.46 GHz, respectively. 'α' is the spectral index (defined by $S_\nu \propto \nu^\alpha$) between 4.86 and 8.46 GHz.

Table 1 shows the temporal variation of α (measured between 4.86 and 8.46 GHz); this quantity shows wild variations during the first few weeks, the period during which the largest flux variations are seen. At later times, when the fluctuations in flux density have dampened, α has settled to a positive value near 0.2. This predicts that the plateau value of the flux at 1.43 GHz will be smaller than that at 8.46 GHz by a factor of 1.4.

We now interpret the radio data in the context of theoretical models proposed for GRBs. Cosmological models of GRBs—so-called "fireball" models—consider the evolution of 10^{52} erg of energy (the energy implied[15] by the minimum distance[8] to GRB970508) that is deposited either impulsively or over timescales typical of the durations of γ-ray bursts. This energy is rapidly converted to kinetic energy which results in a spherical blast wave moving at relativistic speeds. Lorentz factors for the blast wave (Γ) between 300 and 1,000 are invoked. X-ray, optical and radio emission on a timescale longer than the durations of the GRBs (following the γ-ray burst) are generic predictions[16–18] of the fireball models. The afterglow emission arises from synchrotron emission from the particles shocked by the blast wave. The X-ray and optical afterglow of GRB970228, especially its decay, appear to fit a simple formulation of this model[19].

But contrary to the expectation of the simple fireball model, the optical and radio afterglow of GRB970508 shows a slow rise to a plateau value before a decay sets in. Furthermore, the radio plateau value is $\sim$600 μJy, which is an order of magnitude larger than the peak[9] optical value of 50 μJy. Vietri[20] explains these observations by invoking a radial dependence of the density of ambient gas (circumstellar matter) into which the blast wave is expanding. Waxman[15] attributes these to the presence of a low-energy tail of electrons in the post-shock gas (which certainly exist but are ignored in the simplest fireball model). We are in the process of carrying out a comparison of the data presented here using these two models; this analysis will be presented elsewhere.

The observed rapid radio flux variations (Fig. 1a; especially in the first three weeks) and the accompanying dispersion in the spectral-index behaviour find no explanation in fireball models. This is simple to understand as temporal evolution of the fireball is determined by the bulk Lorentz factor, Γ, which smoothly decreases with time. An independent observation providing evidence against intrinsic variations is that there are no reported measurements of such deep and rapid variations at optical wavelengths. Thus to understand these observed variations one must appeal to extrinsic causes.

Goodman[21] has called attention to the potential role of interstellar scattering (ISS) in the variation of the observed radio fluxes. Irregularities in the interstellar medium scatter the incoming radio signal which then results in 'twinkling' of radio sources. There are two basic regimes of ISS[22]: weak and strong. The relevant physical parameters are the Fresnel scale, r_F (the radius of the first Fresnel zone at the interstellar scattering layer, typically assumed to be located at distance $d \approx 1$ kpc from the observer) and the spatial coherence scale of the irregularities, r_c. When $r_c \gg r_F$, the effects of scattering are weak and therefore modest fluctuations in the flux are expected to be observed. In the strong scattering regime ($r_c \ll r_F$) scattering takes place owing to inhomogeneities on scales of r_c (diffractive) and also on much larger scales, r_F^2/r_c (refractive). However, refractive scattering results in modest flux variations and is broad-band in nature.

The observed deep modulation that is seen in the 8.46-GHz data (Fig. 1a), and the wild swings in spectral index, bear the signature of diffractive scintillation. If we accept this conclusion then θ_S, the angular size of the source, must be less than the 'diffractive' angle, $\theta_d = r_c/d$. For typical ISS parameters[21] and an observing frequency of 8.46 GHz, $\theta_d \approx 3$ microarcseconds (μas). From observations of pulsars it is known that the irregularities in the Galactic interstellar medium vary from one line-of-sight to another. For this reason, we point out that the precision of the value quoted for θ_d is unlikely to be better than a factor of two. The minimum redshift of GRB970508 is $z = 0.835$ (ref. 8). Taking a value of 60 km s^{-1} Mpc^{-1} for the Hubble constant, we find a distance $D \approx 10^{28}$ cm. Thus the linear size of the source must be less than $R \approx 10^{17}$ cm.

The variations in the flux of the source appear to moderate after the first month. In the framework of ISS, the source has expanded to

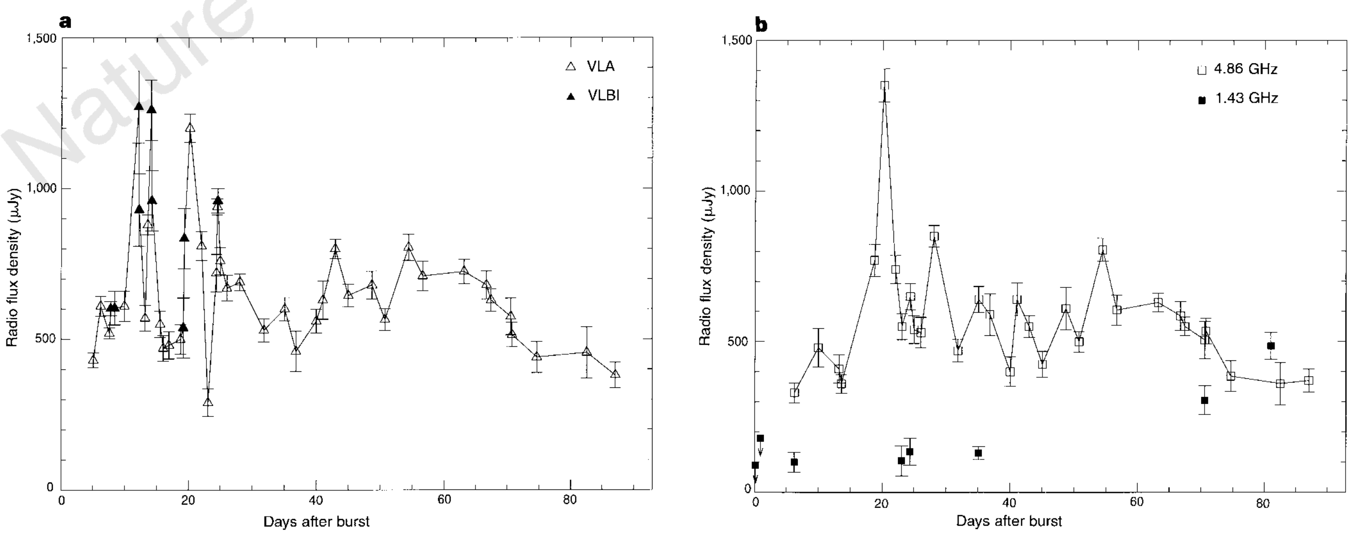

Figure 1 Light curves of the radio counterpart of GRB970508. **a**, Light curve at 8.46 GHz. Data points consist of VLA (open triangles) and VLB data (filled triangles)[23]. The flux densities from the VLB measurements[25] were determined by splitting each data set in half and measuring them independently. There is close agreement between those flux densities which were independently measured by the VLA and VLB. The first detection of the source was made on May 13.96 UT, 5 days after the GRB event. The delay, if any, between the onset of the radio emission and the high-energy radiation is not well constrained, as the earliest VLA observations were made at 1.43 GHz. Unfortunately, as shown in **b** and Table 1, the source was weak for the first month at this frequency. **b**, Light curve at 4.86 GHz (open squares) and 1.43 GHz (filled squares). The sampling at 4.86 GHz is sparser than at 8.46 GHz but the general characteristics of the light curve remain the same, with a plateau or a slight rise in the mean flux density and occasional 'flares'. At 1.43 GHz the source remained weak or undetectable for the first month but has since risen to a level comparable to the plateau values seen at 4.86 and 8.46 GHz.

a large enough size that diffractive scattering is quenched. Goodman[21] points out that refractive scintillation will dominate the scattering. For the parameters discussed above (8 GHz, typical high-latitude line-of-sight) the Fresnel angle, r_F/d, is coincidentally close to θ_d. When the fluctuations are dying down, the source must have a size comparable to θ_d. Goodman[21] shows that in this regime the modulation index (the r.m.s. of the fluctuations to the mean value) is $\sim$12%—precisely what is observed. Moreover, the fluctuations are expected to be broad-band as is indeed the case (see Fig. 1a). Consistent with this discussion, very long baseline (VLB) observations[23] show that the size of the source is $<260\,\mu$as.

We recognize that the above conclusions rest crucially on the assumption that the flux variations are induced by ISS. We now discuss additional evidence for (or against) this assumption. In the ISS framework, flux will vary on a timescale determined by the crossing time of the irregularities, $t_{ISS} \approx r_c/v_E = d\theta_d/v_E$ where v_E is the velocity of the irregularities with respect to the Earth. The differential delay between rays converging to the observer is $d\theta_d^2/c$ and thus the bandwidth of a constructive (or destructive) interference is $\Delta\nu_{ISS} \approx c/2\pi d\theta_d^2$. For our nominal value, $d = 1$ kpc, $\theta_d = 3\,\mu$as (in the 8-GHz band) and $v_E \approx 30\,\mathrm{km\,s^{-1}}$, we obtain $t_{ISS} = 4$ h and $\Delta\nu = 7$ GHz. The VLA data presented here (Table 1) are too poorly sampled to measure t_{ISS}. However, the VLBA data presented by Taylor *et al.*[23] are of longer duration. A 25% variation is seen over 5 h which suggests that $t_{ISS} < 1$ d. The wild variations seen in α (between 4.86 and 8.46 GHz; Table 1) requires that $\Delta\nu \lesssim 2$ GHz. These are not severe disagreements. Both the definitions and the estimates for the two parameters discussed above are approximate. Further improvement in a quantitative sense is best done by carrying out ISS observations of pulsars and compact objects in this part of the sky and obtaining estimates of θ_d, d and v_E in a consistent manner.

An independent estimate for the size comes from an argument presented by Katz and Piran[24]. We have had noted above that in the first month VLA J065349.4 + 791619 is essentially undetectable at 1.4 GHz but strong at higher frequencies. A simple interpretation is that VLA J065349.4 + 791619 is optically thick at 1.4 GHz in the first month. If so, the spectrum expected below the self-absorption frequency is[24];

$$S_\nu = 2\pi\nu^2 m_p \zeta(1+z)R^2/D^2$$

where ζ is a parameter which describes the degree of electron equipartition in the shocked gas, and m_p is proton mass. Fireball models usually (for example, ref. 15) adopt a value of 0.1 for this parameter. Using the measured value of the flux at 1.43 GHz (Table 1), Katz and Piran[24] obtain $R \approx 10^{17}$ cm.

The interpretation of R defined above is unfortunately not a simple matter. What is more interesting is that the above equation predicts that the flux at 1.4 GHz should increase as θ_S^2. Earlier we argued that the source must have significantly expanded between the first and the last month of observations. In accordance with our expectation, we note that the 1.43-GHz flux has increased from $<100\,\mu$Jy to 500 μJy during this period. Taken at face value, this suggests that θ_S has doubled in size over this period. This conclusion is in accordance with our assertion (from interstellar scintillation arguments) that the source has expanded considerably.

We have reported above the first measurement of the linear size of a fireball. From this we can extract the mean Lorentz factor of the expansion. Taking the above-mentioned size of 3 μas for the fireball at about $t = 2$ weeks post-burst, we can obtain a mean speed of the burst, R/t, of $4c$. For a relativistically expanding fireball, $R = f\gamma^2 ct$ and the apparent size is R/γ. Here γ is the Lorentz factor for the expanding shell, and the factor f depends on the dynamical details of the expanding fireball and varies between 2 and 14 (ref. 24). Thus $f\gamma \approx 4$, that is, the shell is mildly relativistic two weeks following the burst. □

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Position and parallax of the γ-ray burst of 8 May 1997

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γ-ray bursts (GRBs) have puzzled astronomers for almost three decades, primarily owing to the lack of identifications at other wavelengths. The detection of a radio counterpart[1] enables application of the powerful technique of very long baseline interferometry (VLBI) to this intriguing class of objects. Here we present VLBI monitoring of VLA J065349.4 + 791619 obtained between 8 and 25 days after the initial γ-ray burst. The radio emission is found to be very compact, with an angular extent of less than 1 milliarcsecond. We derive a position for the radio counterpart accurate to 200 microarcseconds, and constrain the proper motion of VLA J065349.4 + 791619 be less than 50 milliarcseconds per year. We place an upper limit on the annual parallax of 1 milliarcsecond. These results are entirely consistent with the expectations of cosmological models.

On 16 May 1997 UT we started a programme of observations of the radio counterpart to GRB970508, VLA J065349.4 + 791619, with the 10-antenna Very Long Baseline Array (VLBA) spanning the United States. The first observation was conducted 7.8 d after the γ-ray burst and also included the 100-m reflector at Effelsburg, Germany and the Very Large Array (VLA). All the observations were conducted at a central frequency of 8.41 GHz. Signals in both senses of circular polarization were recorded on magnetic tapes and