VLBA observations of the Radio Counterparts to γ-Ray Bursters

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Abstract. The detection of a radio counterpart to GRB 970508 by Frail et al. (1997) opens the way to applying the powerful technique of Very Long Baseline Interferometry to this intriguing class of objects. We demonstrate the applicability of this technique to GRB 970508. Using the Very Long Baseline Array (VLBA), including the phased VLA and the 100-m radiotelescope at Bonn, we were able to image the radio counterpart of GRB 970508 at a resolution of 1 mas. This 8.4 GHz image revealed GRB 970508 to be very compact (less than 400 micro-arcsecond in angular size). We present the results from an ongoing VLBA monitoring campaign of GRB 970508 that commenced 8 days after the initial gamma-ray burst and is still underway 120 days after the burst. We derive a position for the radio counterpart with a standard deviation of 73 micro-arcsecond, and will discuss the limits on proper motions and source expansion obtained so far. Assuming that the radio emission arises from the afterglow of a cosmological fireball, VLBI observations of GRB 970508 and future GRBs offer a reasonable hope of directly measuring the expansion.

INTRODUCTION

The Very Long Baseline Array (VLBA) is the first array of antennas devoted full-time to Very Long Baseline Interferometry (VLBI) observations. As such it is well suited to Target of Opportunity projects. On May 16, 1997 UT we initiated a program of observations of the radio counterpart to GRB 970508, VLA J065349.4+791619 with the 10-antenna VLBA. The first observation was conducted 7.8 d following the gamma-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 using a bandwidth of 32 MHz. Signals in both senses of circular polarization were recorded on magnetic tapes and processed at the VLBA correlator in Socorro, New Mexico. Results from the first 6 epochs have been published in Taylor et al. [1]. Here we discuss the combined results from the 9 epochs obtained to date.

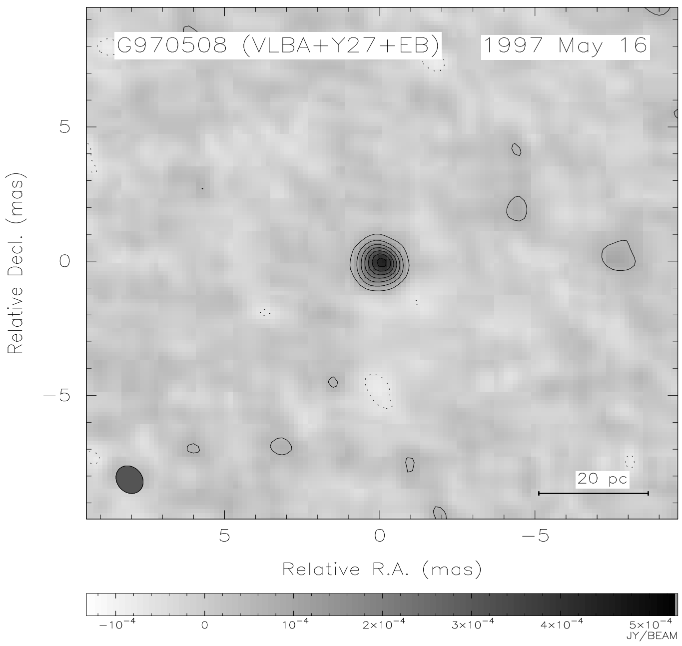

FIGURE 1. The first VLBI observation of VLA J065349.4+791619 on May 16.48 – 16.92 using the VLBA, phased VLA, and 100-m at Effelsburg at 8.4 GHz. Contours are overlaid on a greyscale total intensity image at −60, 60, 120, 180, 240, 300, 360, and 420 μJy/beam.

The atmosphere affects the phase of the signal from the source differently at each of these widely spaced antennas. In order to overcome this and other instrumental contributions we alternated observations of VLA J065349.4+791619 with an observation of the strong, compact "calibrator" source B0718+793 located 1.5° away. This technique, known as phase-referencing, is now routinely used for observations of faint sources with the VLBA. The switching time for the first and sixth epochs (involving the phased VLA) was 2 minutes and 1.5 minutes for all other epochs. VLA J065349.4+791619 was clearly detected in all the nine epochs. In all the nine images, VLA J065349.4+791619 is unresolved, although the final resolution of the instrument depends on the antennas involved and the degree to which atmospheric phase fluctuations could be removed (the latter effect is somewhat analogous to the phenomenon of optical "seeing").

Under the best observing conditions (May 28.4 UT) we place a limit on the source size (defined as the full width at half maximum), $\Delta\theta < 0.26$ milliarcsecond (mas). The corresponding lower limit on the brightness temperature $T_B = S\lambda^2/2k\Delta\Omega$ is 1.4×10^8 K; here $\lambda = 3.6$ cm is the wavelength of observation, k, the Boltzmann constant and $\Delta\Omega = \pi\Delta\theta^2/4$ is the solid angle of the source. Within the measurement errors, there is no indication that the source has expanded to a size approaching the resolution of this experiment.

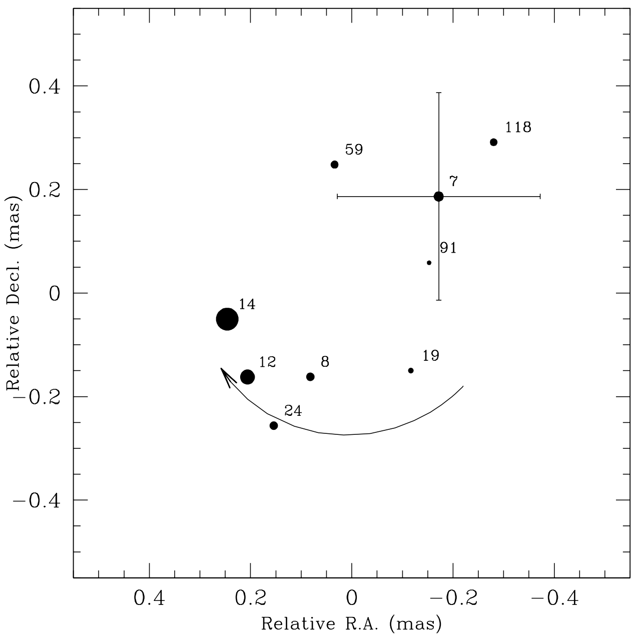

FIGURE 2. Positions of VLA J065349.4+791619 from the 9 VLBI epochs. The zero point was selected to be the fitted position reported in the text. The symbol size is proportional to the upper limit on the source size derived from each observation and the time elapsed in days since GRB 970508 was detected by BeppoSAX is shown next to each measurement. The curve shows the portion of the trigonometric parallax ellipse tracked by an object at 3.3 kpc over the 4 months spanned by our observations.

The deepest image (May 16.7 UT – Fig. 1.) allows us to limit the extended emission on scales 10 mas – 20 arcsec to less than $\sim$50 μJy.

From analysis of the positions of VLA J065349.4+791619 over the nine epochs (Fig. 2) we find: (1) The mean position for VLA J065349.4+791619 is $\alpha = 06^{\rm h}53^{\rm m}49^{\rm s}\!.45133$ and $\delta = +79^\circ16'19''\!.51360$. The 1-$\sigma$ error in $\alpha\cos\delta$ is 73 μas and 73 μas in δ. This position is referenced to the absolute coordinates of the calibrator, 0718+793 [2]. (2) We fit a linear model with astrometric parameters α, δ, μ_α, and μ_δ to the data and place a 3–σ upper limit on the proper motion of $\mu < 5$ mas yr^{-1}. (3) Assuming no proper motion, our limit on the annual trigonometric parallax is $\Pi < 0.3$ mas. This limit requires the distance of the radio source to be greater than 3 kiloparsec. If both parallax and motion are allowed then the limits are somewhat larger.

The radio emission may originate with the explosive event that produced the γ-ray, X-ray and optical transients, or it may be associated with the host galaxy of GRB 970508. Here we compare the radio properties of VLA J065349.4+791619 to those of both "normal" and "active" galaxies, before going on to explore the predictions of cosmological fireball models.

At the sub-mJy level, extragalactic sources are identified with host galaxies having a median optical magnitude V = 23 [3]. The median angular size in the radio of these sources is 2.6 arcsec, and in 90% of the population the radio emission is thought to be a combination of steep-spectrum synchrotron emission from a galactic disk and thermal-bremsstrahlung from large-scale star formation. About 10% of the sub-mJy population may be dominated by emission from a nuclear starburst or a weak Active Galactic Nucleus (AGN). Our VLBI brightness temperature limit of $>10^8$ K rules out galactic disks and star formation as the source of the radio emission from VLA J065349.4+791619.

Next we consider the possibility that the radio emission from VLA J065349.4+791619 originates from the central engine of an AGN. The radio power of the source at a rest frequency of 17 GHz (for an assumed redshift of 1 and $H_0 = 75$) is 10^{24} W Hz^{-1}. This is comparable to the radio powers of nearby low-luminosity AGN [4]. These FR I type radio sources, however, are generally dominated by emission from extended radio lobes. In the few cases where the cores are sufficiently strong, VLBI observations have revealed considerable structure [5]. In most cases this structure has a surface brightness a factor of 20-80 below that of the peak, so it is difficult to make a direct comparison to VLA J065349.4+791619 as at best we have a peak to rms noise level of 20:1 (Figure 1).

The positive radio spectrum of VLA J065349.4+791619 [6], on average, resembles that of the so-called "GHz-peaked" radio sources (GPS). However, these sources show little variability, rather complicated structure on the parsec scale and have bright optical hosts [7,8]. Gravitationally lensed sources at similar redshifts may have a comparable intrinsic radio power, but these also show much less radio variability than GRB 970508, from 0 to 10%. The morphologies of the gravitationally lensed sources are predominantly core+jet [9,10]. The extreme variability of VLA J065349.4+791619 [6] is characteristic of a class of radio sources known as intraday variables (IDVs), but these originate in flat-spectrum radio sources such as BL Lacs and quasars [11].

The radio data on VLA J065349.4+791619 – (*i*) the small angular size and correspondingly high brightness temperature, (*ii*) the steep, positive spectral index and high variability, (*iii*) the absence of any diffuse or jet-like emission around the central source and (*iv*) the lack of proper motion and parallax – are not commensurate with any known population of radio sources but they are consistent with the expectations of all cosmological fireball models.

Optical observations of the galaxy in which this radio source is located are also relevant. The optical source continues to fade and as yet there are no indications of any host galaxy to a limit of about R=24.5 mag [12]. This rules out the radio source being a GPS, IDV or FR I source since the host galaxy of these objects would be bright. Thus the observations support the idea that the radio source reported here is not a typical extragalactic radio source embedded in the central portions of a host galaxy. The preferred interpretation, consistent with the optical spectroscopy, is that GRB 970508 is a fireball located in a low luminosity blue galaxy [12].

Proceeding with the hypothesis that VLA J065349.4+791619 is the radio afterglow from GRB 970508 it is interesting to note that our observations rule out significant gravitational lensing on scales of 10 mas – 300 arcsec. This covers the range of lenses discussed in the literature and rules out any substantial flux magnification of the γ-ray burst by gravitational lensing.

The VLBA observations reported here had typically longer durations than the VLA observations of Frail et al. [6], and thus can be used to probe variability on timescales of hours. During the three observations between May 21 and May 28, significant flux density variability was detected within each 5.6 hour run at the level of 10-20%/hour. This data is plotted in figure 1 of Frail et al. where it is explained as the result of diffractive interstellar scintillation.

In the future, an afterglow with the same radio luminosity as GRB 970508 but at z=0.2 could be 30 times brighter and have an angular diameter twice as large. This would improve the obtainable limits on source size by over a factor of 50 and open the way for using VLBI to study the detailed evolution of a resolved GRB in much the same way as has recently been done for extragalactic supernovae [13]. If θ remains small, then as discussed in [6], there is great potential for using less direct methods such as interstellar scintillation to determine the evolution of the fireball.

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