Astron. Astrophys. 321, 229–235 (1997)

ASTRONOMY AND ASTROPHYSICS

Two variable radio sources near the position of GRB 940301

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Received 19 July 1996 / Accepted 7 October 1996

Abstract. We report on the results of a search for a radio counterpart to the strong gamma-ray burst GRB 940301. Observations with the Westerbork Synthesis Radio Telescope of the Compton Telescope error box region of GRB 940301 began on March 4, 1994, at 21 cm and April 2, 1994, at 92 cm. No flux density variations were detected at 92 cm above S = 10 mJy (5 σ) within a period of 1 to 4 months after the burst. However, when we compared the field with Westerbork Northern Sky Survey data, taken two years prior to GRB 940301, we found two radio sources with significantly increased flux densities. These sources, only 17′ apart, are located at the 2.3 and 2.6 σ Compton Telescope confidence contours. Their separation from the Inter Planetary Network annulus virtually excludes association with GRB 940301. Further observations in January 1996 reveal that the sources continued to change in flux density. The relatively large flux density variations at 92 cm, compared to those at higher frequencies, and the inverted spectra in the frequency range from 325-380 MHz make the sources somewhat unusual. Because the sources were already detected at 5 GHz in 1986 most, if not all, of the radio emission is probably associated with activity in Active Galactic Nuclei in distant galaxies.

Key words: gamma rays: bursts – techniques: interferometric

1. Introduction

Observations with the Burst And Transient Source Experiment (BATSE), aboard the Compton Gamma-Ray Observatory (CGRO), have shown that the distribution of gamma-ray bursts (GRBs) is isotropic on the sky and inhomogeneous in space. The main problem in studying the nature of GRBs is that their distance scale is not known; some argue that GRBs originate from a large halo around our Galaxy (e.g., Brainerd 1992; Eichler and Silk 1992), others that they come from "cosmological" distances (e.g., Paczyński 1986, 1991, 1995; Piran 1995). The identification of a counterpart to a GRB at other wavelengths could provide an answer to this question. So far, no firm counterpart to a GRB at other wavelengths has been identified. Two strategies have so far been employed for counterpart searches. Deep searches for quiescent counterparts to accurately localized events, i.e., for low energy emission long after the burst, have been made; but no quiescent counterparts have so far been detected, at all photon energies (e.g., Schaefer 1993). Another strategy has been to search for flaring counterparts in simultaneous wide-field monitoring experiments in the hope to have a GRB in the field of view of the instrument at the moment of the event. Recently, searches for faint counterparts have been made which started within hours or days of the event (e.g., Frail et al. 1994). The GRB detection is used as a trigger to point the telescope in the appropriate direction and search for a flaring and/or fading counterpart on timescales much longer than the burst itself. The incentive for such a counterpart search is provided by fireball models (e.g., Rees and Mészáros 1992; Mészáros and Rees 1993; Paczyński and Rhoads 1993; Piran 1995), that predict a transient delayed radio counterpart. For bursts at cosmological distances the delay at cm-dm wavelengths could be weeks to months or even years. Radio observations provide a good possibility to identify a GRB with its transient radio counterpart (and accurately determine its position). In this paper we present the results of a radio search for variability in the Compton Telescope (COMPTEL) error region of GRB 940301. Information on this GRB is given in Sect. 2. The observations and their reduction are described in Sect. 3. The analysis of the data and search for variability is described in Sect. 4. The observa-

Send offprint requests to: T.J. Galama tional results on two variable sources are given in Sect. 5, and the more general and speculative aspects of the interpretation are discussed in Sect. 6. Sect. 7 contains our conclusions.

2. GRB 940301

On 1994, March 1st at $20^h 10.6^m$ UT a strong gamma-ray burst occurred (GRB 940301), lasting ~ 40 s. The burst was recorded by BATSE and COMPTEL. With a fluence of 3.5×10^{-5} erg cm^{-2} (50-300 keV) it belongs to the 2 % brightest bursts detected with BATSE. The COMPTEL localization and the Inter Planetary Network (IPN) annulus (derived from the time difference between the detection on board of the Compton Gamma-Ray Observatory, CGRO, and the Ulysses spacecraft; the plotted IPN is an improved determination, Hurley, private communications) can be seen in Fig. 1.

Because of the high declination of GRB 940301 it is a favorable target for the Westerbork Synthesis Radio Telescope (WSRT). Furthermore, GRB 940301 is located well out of the galactic plane: $(l^{II}, b^{II}) = (151°, +24°)$.

GRB 940301 triggered an extensive multi-wavelength campaign with ground based optical and radio observatories from the BATSE/COMPTEL/NMSU Rapid Response Network (RRN; e.g., McNamara et al. 1995), of which Westerbork is a member.

The positional error box of this burst was also covered in observations by Frail et al. (1994; Penticton) and Koranyi et al. (1995; Cambridge) but no obvious candidate counterparts were reported by these authors. So far no identification of an optical or radio counterpart to the GRB 940301 has been made by the RRN (Harrison et al. 1995). The WSRT 325 MHz observations, which are an order of magnitude more sensitive than the low-frequency observations made with the Penticton (408 MHz) and Cambridge (151 MHz) arrays, revealed two variable radio sources. Preliminary results from the WSRT observations were presented in Hanlon et al. (1995).

3. Observations and data reduction

Observations with the WSRT of the combined COMPTEL and IPN error region (from now on referred to as COMPTEL+IPN) of GRB 940301 began, three days after the first of March event, at 1400 MHz (21 cm). Data were recorded in 8 spectral bands with a total bandwidth of 65 MHz (5 bands with a width of 10 MHz at 1375, 1385, 1395, 1405 and 1415 MHz, and 3 bands with a width of 5 MHz at 1367.5, 1397.5 and 1423.5 MHz). Full polarisation information was recorded. Observations were obtained at several pointings (fields 1 to 5, A and B in Fig. 1). The COMPTEL+IPN error region is not fully covered at 21 cm (see Fig. 1). Coverage of the whole COMPTEL+IPN error region was not obtained until 32 days after the occurrence of the event, by which time the operating wavelength had changed to 92 cm.

The 92 cm broad-band data cover a total continuum bandwidth of 40 MHz, recorded in 8 bands each 5 MHz wide, centered at 319.3, 325, 333, 341, 355, 360, 375 and 380 MHz (these bands correspond to wavelengths 94 → 79 cm). Henceforth we will refer to these data as the 92 cm data. A total of 48.8 hours of data were taken in 9 observations, covering the period from April 2 until June 25, 1994; additional observations were obtained January 15 and 16, 1996 at slightly different band frequencies. Table 1 provides a log of the data. Full polarisation information was measured, but no polarisation was detected from any of the interesting sources. Due to interference about 20 % of the data were unusable. This interference was usually concentrated in a few bands. The data were reduced using the Netherlands East-West Synthesis Telescope Array Reduction package (NEWSTAR) [1].

Because of incompleteness of the $u - v$ coverage of the 92 cm observations that last less then 12 hours, we combined data from April 2 1994 with data from June 25 1994, which, together, yielded almost a complete 12^h synthesis. From these data we constructed an accurate model of the field at 92 cm in a number of steps. We began with calibrating the complex gains for each observation and each band, using the calibrator sources 3C48, 3C147 and 3C286. For these primary WSRT flux calibrators we adopt flux densities of 46.1, 56.7 and 26.9 Jy at 325 MHz and spectral indices α_s = –0.65, –0.62 and –0.35 in the range 300-400 MHz (where spectral index α_s is defined by $\alpha_s = d \log S / d \log \nu$). The data were then self-calibrated in phase using a model of the field obtained from the initial data. This process was iterated a few times and thereby the model refined until nearly 400 discrete background sources above a flux density of about 6 mJy were included in the model. The excellent $u - v$ coverage resulting from the wide range in frequencies resulted in a very low sidelobe level in the synthesized beam, a property essential to imaging of a wide field with many hundreds of sources. The total flux density in the model is 19 Jy with 5 sources in the range from 0.5 to 1 Jy. The relatively large spectral baseline in the 92 cm data allowed us to also solve for the spectral index of each source in the field.

4. A search for variability

We searched for a transient radio counterpart by looking for variability within the COMPTEL+IPN error region on three distinct timescales: long-term variations (about two years), variations within the period of the 92 cm observations (about three months) and short-term variations within a single observation (hours). Long-term variations were searched for by comparing the images of the 92 cm observations with those obtained for the Westerbork Northern Sky Survey (WENSS) [2]. The WENSS observations of the area around the position of GRB 940301 were taken during a period of 2 months more than 2 years before the GRB 940301 event.

We combined observations of GRB 940301 of April 2 and 11, and June 5, 11 an 25, 1994, and made a map of the 325 MHz data of these observations. These particular observations were chosen because of the quality of the data, the good $u-v$ coverage

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

[2] http://www.strw.LeidenUniv.nl/wenss/

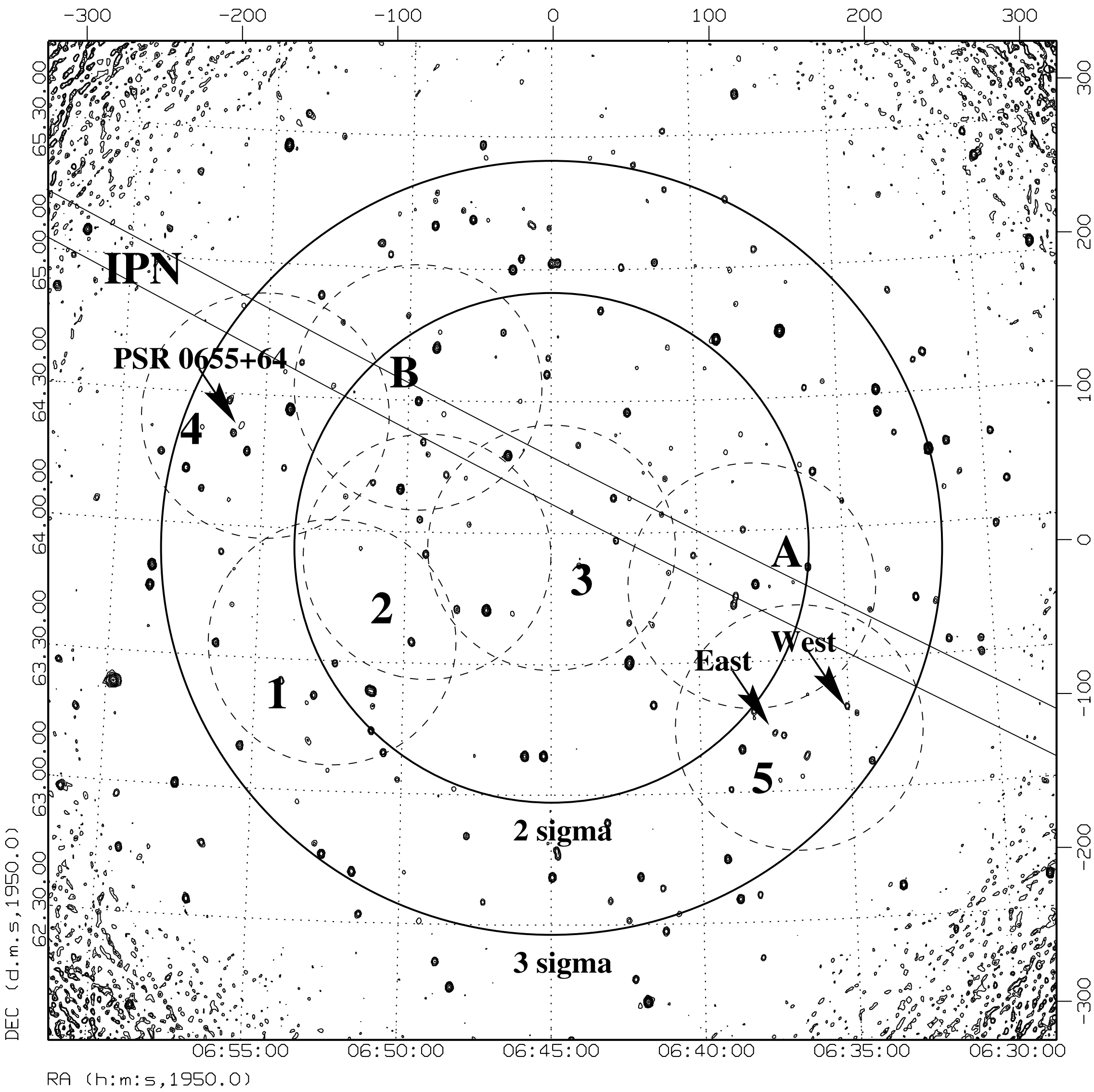

Fig. 1. Contour plot of the WSRT image at 325 MHz (April-June 1994) of the GRB 940301 field centered at $06^h\ 44^m\ 55.7^s$, $63^\circ\ 58'\ 37.6''$ (equinox B1950). Included are the 2 and 3 sigma COMPTEL error regions, the IPN triangulation annulus (radius + 3σ and radius -3σ), and the 21 cm fields 1, 2, 3, 4, 5, A and B at 20% response. Indicated are the positions of PSR B0655+64, the East source (B0637+6313) and the West source (B0635+6318). Contour levels are 15, 30, 60, 120, 240, 480, 960 and 1510 mJy. The increase in noise at the edge of the field is due to primary beam correction.

and because the WENSS survey was also done at 325 MHz. We obtained a difference map by subtracting the WENSS image (mapped onto an identical grid and corrected for the different primary beams) from the GRB 940301 image. In this way we found two objects that showed a very large increase in their flux density. Within an area of about 4° diameter around the COMPTEL position these two sources were, in fact, the only ones showing a variation larger than 5% or a variation in excess of 5 times the noise. The brightest sources in the field typically agreed to within 1-2%.

We also searched for variability within the three month period of the 92 cm observations. Unfortunately, our observations are of various durations and were obtained with different configurations of the Westerbork array. Hence, the synthesized beams of the different images differ. The most sensitive way to look for variations in the data is via the construction of difference maps from residual maps, i.e. maps deconvolved with a model containing all real sources in the field. We proceeded as follows. We obtained equal synthesized beams in the residual maps of two observations by retaining only those $u - v$ points in common to both datasets. Subsequently, we subtracted the two maps from each other and obtained the difference map. We considered only pairs of observations that have at least two hours of overlap in hour angles. In these difference maps we did not detect any source variation above 10 mJy (5σ), within the 92 cm period of observations (1 to 4 months after the GRB). The two

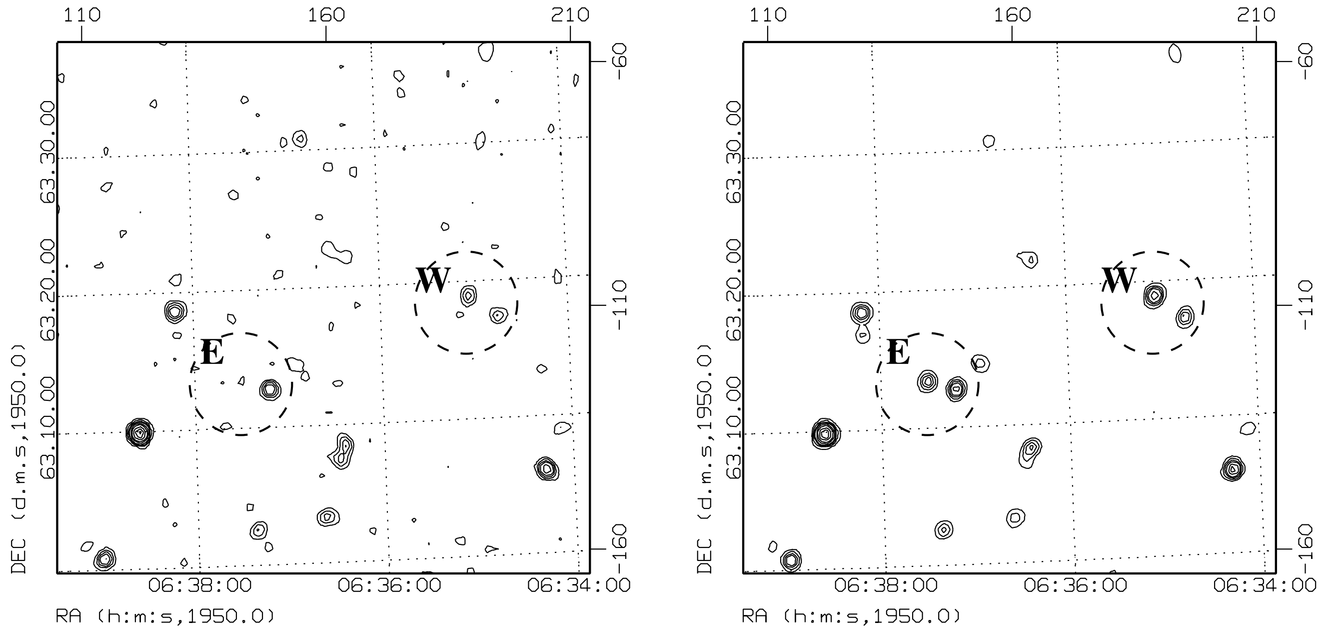

Fig. 2. Contour plots, of the East and West variable sources, of WSRT images at 325 MHz from WENSS (left-hand side) and from the GRB 940301 field (right-hand side). Contour levels are 7.5, 15, 22.5, 30, 45, 60, 90, 120, and 150 mJy. The map noise levels are 4 and 1.4 mJy, respectively, corrected for primary beam attenuation.

Table 1. Broad-band 92 cm WSRT observations.

Day	Duration (h:m)	MJD[a] (start)
Apr. 2, 1994	5:16	49444.537
Apr. 11, 1994	3:10	49453.774
May 2, 1994	2:08	49474.739
May 20, 1994	2:20	49492.758
June 5, 1994	4:45	49508.614
June 11, 1994	4:53	49514.463
June 13, 1994	3:54	49516.322
June 20, 1994	5:05	49523.559
June 25, 1994	6:15	49528.494
Jan. 15, 1996	6:09	50097.942
Jan. 16, 1996	5:00	50098.789

[a] MJD = JD - 2400000.5

sources found by comparison with the WENSS data, were not conspicuous in these difference maps.

Finally, we searched for variability on timescales of hours by looking for the characteristic artifacts that such rapid variations can cause in the case of a 1-dimensional earth-rotation synthesis instrument (see e.g. Van den Oord and De Bruyn 1994). In the June 26 1994 data we discovered a rapidly variable radio source which turned out to be associated with the nearby binary pulsar PSR B0655+64 which is located only 1.25° from the pointing centre. These results are described in more detail in Galama et al. (1997).

5. Two variable radio sources

The two variable sources (B0637+6313 and B0635+6318, hereafter referred to as the East and West source), are located at the edge of the synthesized field at 92 cm (which measures about 2.7° at 325 MHz at half-power). They are only 17′ apart. Both sources are unresolved in the 92 cm (55″ beam) and 21 cm (13″ beam) observations. From a full 12 hour run at 21 cm we obtained accurate positions of both sources at $6^{h}37^{m}29.91^{s} \pm 0.07^{s}$, $+63°13'26.1'' \pm 0.5''$ (East source) and $06^{h}35^{m}03.26^{s} \pm 0.07^{s}$, $+63°18'59.3'' \pm 0.5''$ (West source; B1950). They are located at approximately the 2.3 and 2.6 σ confidence contour of the COMPTEL position of GRB 940301, respectively. They fall outside the IPN triangulation annulus for this GRB (the East source by about 9 σ and the West source by about 18 σ, taking half the width of the IPN annulus, 0.045°, as 3 σ; see Fig. 1).

Two contour plots of the area containing the two sources are shown in Fig. 2. The plot on the left-hand side is obtained from the WENSS data, the right-hand plot from our 325 MHz observations, made from data taken on April 2, 11, and June 5, 11, 20 (1994).

The East source was barely detected in the WENSS survey (see Fig. 2). The source continued to increase at 325 MHz until January 15/16, 1996 (see Fig. 3). The total increase between the beginning of 1992 and January 1996 is a factor of $7.0^{+7}_{-2.3}$ (1 σ; henceforth all quoted errors are 1 σ). A summary of all flux densities is given in Table 2.

The source was detected as a radio source well before the time of the GRB. It appears in the GB6 6cm (4850 MHz) survey with the Green Bank telescope (Gregory et al. 1996) and in the

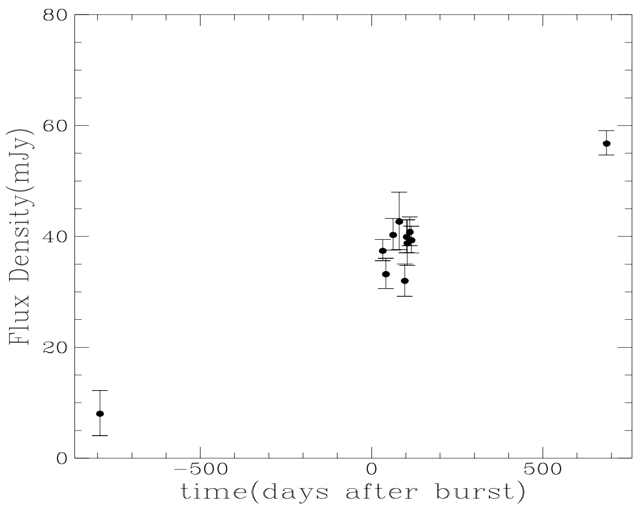

Fig. 3. Light curve of the East variable source at 325 MHz obtained from the 92 cm data.

Table 2. Flux densities for the East source (B0637+6313).

Date	325 MHz flux (mJy)	Survey
Dec. 1991 - Jan. 1992	8 ± 4	WENSS
Apr. - June 1994	39 ± 1	WSRT
Jan. 15-16, 1996	56.0 ± 2.2	WSRT
	1400 MHz flux (mJy)	
Oct. 5-26, 1983	< 50 (2 σ)	Green Bank
Sep.- Nov. 1993	64.8 ± 1.0	NVSS
Sep. 10, 1994	65 ± 15	WSRT
July 7, 1995	44.5 ± 1.1	WSRT
	4850 MHz flux (mJy)	
Oct. 1986 + Oct. 1987	36 ± 5	GB6

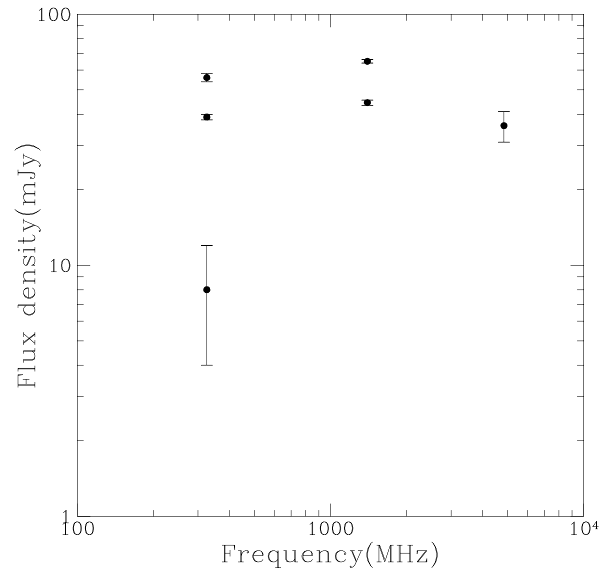

Fig. 4. Broad-band spectra for the East variable source, as obtained from the data in table 2. The axes are chosen in such a way that a +45° slope corresponds to a spectral index of +1.

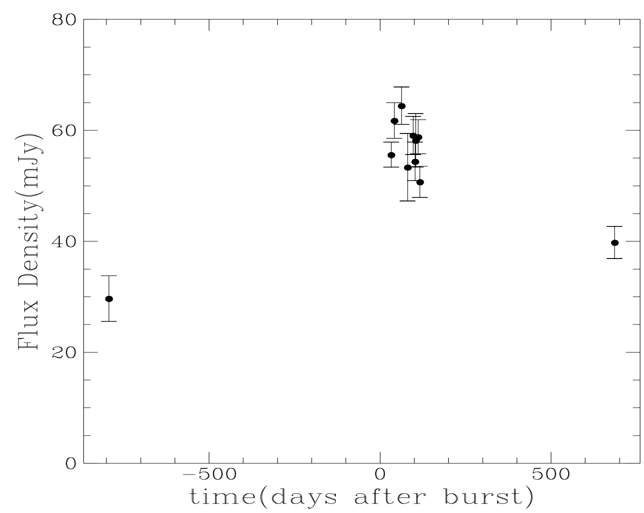

Fig. 5. Light curve of the West variable source at 325 MHz obtained from the 92 cm data.

NRAO NVSS survey at 21 cm (Condon et al. 1996; in progress). There is no source visible in the images from the Green Bank 21 cm survey (Condon and Broderick 1986) down to about 50 mJy. The Green Bank 21 cm survey is, however, confusion limited (1 $\sigma \approx 25$ mJy).

The broad band spectrum of the East source, from 0.3 to 5 GHz, is shown in Fig. 4. Although the data are obtained at different dates it is clear that the overall spectrum is fairly flat as is typical for compact extragalactic radio sources. The flux density in the July 7th, 1995, 1400 MHz observation was of sufficient strength to allow us to derive a spectral index within the 65 MHz wide band: $\alpha_s = +0.25 \pm 0.16$, consistent with the overal spectrum. In the 1994 92 cm data the spectral index of the East source was highly inverted, $\alpha_s = 1.6 \pm 0.4$. In January 1996, when the source had brightened, the spectrum had flattened.

The West-variable source first increased in flux at 325 MHz, compared to the WENSS survey, by about a factor 2.1 ± 0.3 and then declined again by almost the same factor (see Fig. 5 and Table 3). The July 7, 1995 data yielded a flux density at 1400 MHz, nearly identical to the value obtained from the NRAO NVSS survey. From the 21 cm survey with the Green Bank telescope an upper limit of 50 mJy, October 1983, was obtained. Also, this source was detected well before the time of the GRB in the 6 cm Green Bank survey (GB6).

The spectrum of the West source is shown in Fig. 6. The plot reveals that its spectrum is fairly flat ($\alpha_s \sim -0.4$), though again we should note that the data are obtained at different dates. The July 7th, 1995, 1400 MHz observation yielded $\alpha_s = -0.07 \pm 0.26$. In the 1994 92 cm data the spectral index of the West source

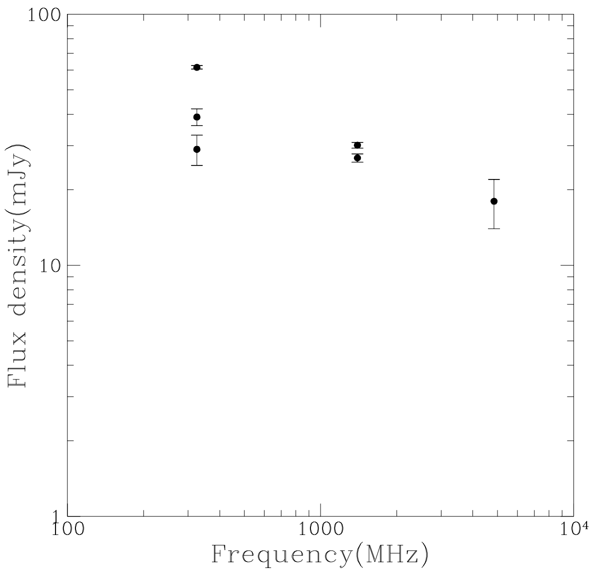

Fig. 6. Broad-band spectra for the West variable source, as obtained from the data in table 3. The axes are chosen in such a way that a +45° slope corresponds to a spectral index of +1.

Table 3. Flux densities for the West source B0635+6318.

Date	325 MHz flux (mJy)	Survey
Dec. 1991 - Jan. 1992	29 ± 4	WENSS
Apr. - June 1994	61.5 ± 1.0	WSRT
Jan. 15-16, 1996	39.2 ± 1.6	WSRT
	1400 MHz flux (mJy)	
Oct. 5-26, 1983	< 50 (2 σ)	Green Bank
Sep.- Nov. 1993	26.8 ± 1.0	NVSS
July 7, 1995	30.1 ± 0.8	WSRT
	4850 MHz flux (mJy)	
Oct. 1986 + Oct. 1987	18 ± 4	GB6

was fairly flat $\alpha_s = 0.2 \pm 0.4$. Also the spectrum obtained from the 92 cm January 15/16 1996 observation is flat to inverted, with a spectral index $\alpha_s = 0.6 \pm 0.5$.

It is remarkable that both the East and West source have inverted spectra at low frequencies. We have therefore paid special attention to the accuracy with which we can determine spectral indices, by analysing the spectra of many, faint and bright, sources in the field. The brighest ten sources in the field have a spectral index from 325-380 MHz of about –0.9, typical for bright extragalactic sources selected at low frequencies. The 62 mJy source only 2′ west of the East source (within the dotted circle in Fig. 3) in fact has an average spectral index between 325 and 380 MHz of –1.9 in the 1994 and 1996 data, which is identical to within the errors to the value between 325 and 1400 MHz, which is obviously determined with much higher accuracy. We have therefore no doubt that these two variable sources have indeed inverted low-frequency spectra.

Neither the East nor the West source has an optical counterpart in the Palomar Optical Sky Survey. They must therefore be fainter than $\sim$ 20th magnitude (O and E). Observations of the East- variable source with the 1 m. JKT telescope at La Palma on 20 November, 1995, revealed a V = 21.0 non-extended object (seeing 1.2″), with a $B - V$ = 0.9, at the exact position of the radio source. Additional imaging of the West variable source with the 1 m. JKT at la Palma during service time observations revealed no optical counterpart down to V = 20.0.

6. Discussion

Although, within an area of about 4° diameter around the COMPTEL position the East and West sources are the only ones showing significant variations, their location at the 2.3 and 2.6 σ COMPTEL confidence contour, respectively, and their separation from the IPN triangulation annulus virtually excludes their association with GRB 940301. We, however, point out that the predictions of the Paczyński and Rhoads (1993) model are that GRB 940301 is followed by a radio flare with a peak flux of 1.4 mJy at 92 cm, 250 days after the event, for a source at a distance of 0.5 Gpc. The time scale is not unlike the variations we have seen. Even though the sources are probably not associated, their variability may be representative of the variations that searches for radio counterparts to GRBs will have to be sensitive to.

Remarkable aspects of both sources, but especially the East source, are their large flux density variation and their inverted low-frequency spectra. From the lack of significant variations in the East source during a period of 3 months in the spring and summer of 1994 it does appear, however, that the flux increase in the East source must have started *before* the time of the GRB. The high 21 cm flux density in November 1993 suggests that an 'outburst' may have occurred somewhere in 1993. Since outbursts are generally delayed at longer wavelengths the start of the 92 cm outburst could have occurred in the beginning of 1994. This would be consistent with the strongly inverted spectral index of the source at that time. The steep spectrum in 1994 is also consistent with most of the emission being due to a 'new' source with little, if any, contamination by an underlying flatter spectrum component, a hypothesis supported by the low 1992 WENSS flux density. The flattening of the spectrum of the East source in January 1996 suggests that the source was approaching its maximum flux density by then.

The West source first increased and then declined by almost the same factor. Also for this source the data in the spring and summer of 1994 do not reveal significant variation. The West variable source also had a flat to inverted spectrum in 1994. In January 1996 this was almost unchanged. The West source therefore showed an outburst of about 20 mJy at 92 cm sometime between 1992 and 1996. There is no evidence for variations of this order at 21 cm.

The fact that fairly flat spectrum radio sources were detected at the location of the two variable sources well before the time of GRB 940301 suggests that the variable radio sources are located in galaxies with Active Galactic Nuclei (AGN) activity and may well originate in these AGN. Studies of Low Frequency Variability (LFV) in complete samples of extragalactic radio sources (e.g., 318 MHz: Dennison et al. 1981; 408 MHz: Fanti et al. 1983; Padrielli et al. 1987) have shown that many compact, flat spectrum, extragalactic sources vary in intensity at meter wavelengths. Typically these variations are of the order 10-50 % on timescales of 1 year. Few sources, however, are reported to have varied by factors of up to 2 or 3 (408 MHz: Hunstead 1972; 318 MHz: Condon et al. 1979; 318 MHz: Dennison et al. 1981). Good data only exist for bright (several Jy) sources. It is generally believed that these low-frequency variations in AGN are due to interstellar refractive scintillation. The spectral behaviour of the East variable during its flux rise is, however, more suggestive of an $intrinsic$ variation. Such variations could be due to a violent event (e.g., a shock) in the core/jet of the AGN. Within the context of the AGN-variability interpretation it does remain unusual, however, that the variations are so large at 92 cm while only modest (East) or small (West) variations have been seen at 21 cm (although we recognize that our time coverage at 21 cm is rather scanty).

7. Conclusions

We conducted a search for variability within the COMPTEL+IPN error region of GRB 940301. No flux density variations were detected above S = 10 mJy (5 σ), within a period of 1 to 4 months after the burst, in the WSRT 92 cm data. However, on a longer timescale we discovered two variable radio sources. The sources fall somewhat outside of the COMPTEL error region. But their separation from the IPN annulus virtually excludes association with GRB 940301. They were the only sources showing significant variations at 325 MHz, within an area of about 4° diameter around the COMPTEL position. Most likely the objects are AGN. The East source revealed an exceptionally large flux-density increase and a spectral behaviour indicative of a 'fresh' outburst.

Acknowledgements. We are grateful for the assistance of the WSRT telescope operator R. de Haan. The WSRT is operated by the Netherlands Foundation for Research in Astronomy (NFRA) with financial aid by the Netherlands Organization for Scientific Research (NWO). T. Galama is supported through a grant by NFRA under contract 781.76.011.

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