

## GRB 030329: 3 years of radio afterglow monitoring

BY A. J. VAN DER HORST<sup>1,\*</sup>, A. KAMBLE<sup>2</sup>, R. A. M. J. WIJERS<sup>1</sup>,  
L. RESMI<sup>2,3</sup>, D. BHATTACHARYA<sup>2</sup>, E. ROL<sup>4</sup>, R. STROM<sup>1,5</sup>,  
C. KOUVELIOTOU<sup>6</sup>, T. OOSTERLOO<sup>5</sup> AND C. H. ISHWARA-CHANDRA<sup>7</sup>

<sup>1</sup>*Astronomical Institute, University of Amsterdam, Kruislaan 403,  
1098 SJ Amsterdam, The Netherlands*

<sup>2</sup>*Raman Research Institute, Bangalore 560080, India*

<sup>3</sup>*Joint Astronomy Programme, Indian Institute of Science,  
Bangalore 560012, India*

<sup>4</sup>*Department of Physics and Astronomy, University of Leicester,  
University Road, Leicester LE2 7RH, UK*

<sup>5</sup>*ASTRON, PO Box 2, 7990 AA Dwingeloo, The Netherlands*

<sup>6</sup>*NASA/MSFC, NSSTC, VP62, 320 Sparkman Drive, Huntsville,  
AL 35805, USA*

<sup>7</sup>*National Centre for Radio Astrophysics, Post Bag 3, Ganeshkind,  
Pune 411007, India*

Radio observations of gamma-ray burst (GRB) afterglows are essential for our understanding of the physics of relativistic blast waves, as they enable us to follow the evolution of GRB explosions much longer than the afterglows in any other wave band. We have performed a 3-year monitoring campaign of GRB 030329 with the Westerbork Synthesis Radio Telescopes and the Giant Metrewave Radio Telescope. Our observations, combined with observations at other wavelengths, have allowed us to determine the GRB blast wave physical parameters, such as the total burst energy and the ambient medium density, as well as to investigate the jet nature of the relativistic outflow. Further, by modelling the late-time radio light curve of GRB 030329, we predict that the Low-Frequency Array (30–240 MHz) will be able to observe afterglows of similar GRBs, and constrain the physics of the blast wave during its non-relativistic phase.

**Keywords:** gamma-ray bursts; radio afterglows; afterglow modelling

### 1. Gamma-ray burst radio afterglows

Radio light curves of gamma-ray burst (GRB) afterglows display a very different behaviour compared with their optical or X-ray light curves (Frail *et al.* 1997). The reason for this is the shape and evolution of the broadband synchrotron spectrum. The broadband spectrum is characterized by its peak flux and the three break frequencies, namely the peak frequency  $\nu_m$  that corresponds to the

\* Author for correspondence (avdhorst@science.uva.nl).

One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.

minimal energy in the electron energy distribution, the cooling frequency  $\nu_c$  that corresponds to electrons that cool on the dynamical time-scale and the synchrotron self-absorption frequency  $\nu_a$ . These break frequencies and the peak flux can be described in terms of the energy in the blast wave, the density of the surrounding medium and the fractional energy in the radiating electrons and in the downstream magnetic field (Wijers & Galama 1999). These four parameters can only be determined if the evolution of all three break frequencies and the peak flux is known, i.e. when well-sampled light curves at X-ray, optical and radio wavelengths are at hand.

In most afterglows,  $\nu_m$  shifts to between the radio and optical regimes within a few hours, which is the usual time-scale for the start of radio afterglow observations, when  $\nu_a$  lies in the radio wave band. Therefore, the evolution of  $\nu_m$  and  $\nu_a$  can only be studied at radio wave bands. However, the synchrotron self-absorption causes a steep spectral decline at long wavelengths, making it difficult to detect radio afterglows at early times. At later times, as the peak of the broadband spectrum moves towards the radio regime, the radio light curve shows a rise, in contrast with the declining light curves at optical and X-ray frequencies. Variations in the temporal slope are caused by the passages of  $\nu_m$  and  $\nu_a$  through the observing bands, and by changes in the dynamics of the blast wave. These changes occur when the relativistic blast wave starts spreading laterally, manifesting as a ‘jet break’ in optical and X-ray light curves, and when the blast wave becomes non-relativistic.

## 2. Gamma-ray burst 030329 afterglow

GRB 030329 displayed one of the brightest afterglows ever, enabling the study of its evolution for a long time and in detail over a broad range of frequencies, from X-ray to centimetre wavelengths. The afterglow was still visible in radio waves 1100 days after the burst trigger. The optical afterglow was visible for only a couple of weeks until it was obscured by the emerging supernova associated with the GRB (Hjorth *et al.* 2003; Stanek *et al.* 2003); the X-ray afterglow was detected for only a few months (Tiengo *et al.* 2004). Thus, using our radio observations we can follow the evolution of the blast wave into the non-relativistic phase and uniquely determine the physical parameters of the blast wave.

The broadband afterglow can be modelled by the standard relativistic blast wave model, assuming either a ‘double jet model’ (Berger *et al.* 2003) or a ‘refreshed jet model’ (Resmi *et al.* 2005). In both the models, the early-time optical and X-ray light curves are explained by a jet with a small opening angle. The double jet model assumes a co-aligned wider jet component that carries the bulk of the energy and produces the late-time light curves. In the refreshed jet model, the initial jet is ‘re-energized’ by the central engine during its lateral expansion, to make it collimated to a wider opening angle. This refreshed jet then produces the late-time emission. Since the peak and self-absorption frequency of the broadband spectrum of either the wide jet component or the refreshed jet are situated in the centimetre regime, this component is naturally best studied at these wave bands.

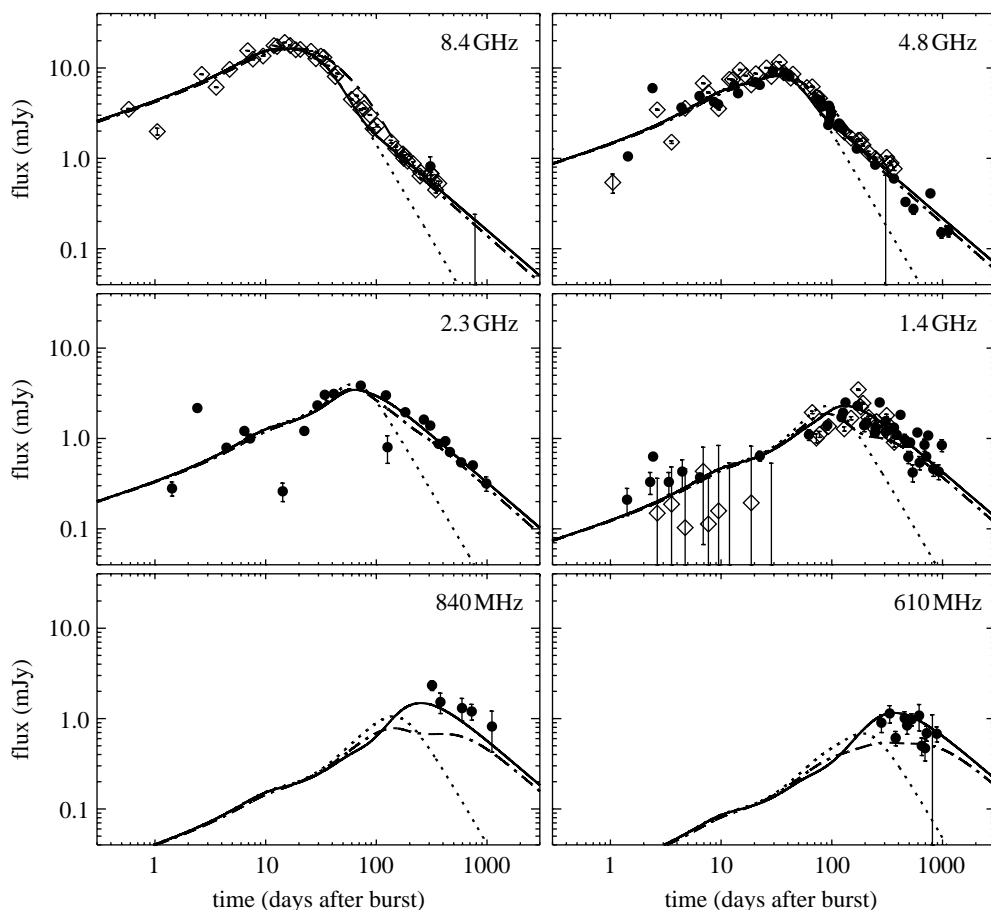


Figure 1. Modelling results of the afterglow of GRB 030329 at centimetre wavelengths. Our light curves obtained with WSRT and GMRT are shown together with earlier reported fluxes from WSRT ([van der Horst \*et al.\* 2005](#)), GMRT ([Resmi \*et al.\* 2005](#)) and VLA and ATCA ([Berger \*et al.\* 2003](#); [Frail \*et al.\* 2005](#)). The filled circles are WSRT and GMRT measurements and the open diamonds are VLA and ATCA measurements. Three fits to the data are shown: the dotted line represents a fit to the first 100 days of radio observations with a wide jet expanding in a homogeneous medium; the solid line corresponds to a model in which the blast wave becomes non-relativistic after 80 days; and the dash-dotted line corresponds to a model in which a third jet component with an even wider opening angle is present. The latter model is excluded by the observations less than 1 GHz, which leaves the model with the non-relativistic phase after 80 days as the preferred model for the late-time behaviour of the blast wave.

### 3. Results of the Westerbork Synthesis Radio Telescope and Giant Metrewave Radio Telescope results

The afterglow of GRB 030329 was observed with the Westerbork Synthesis Radio Telescope (WSRT) and the Giant Metrewave Radio Telescope (GMRT) from 325 MHz to 8.4 GHz, spanning a time range of 268–1128 days after the burst ([figure 1](#); [van der Horst \*et al.\* in preparation](#)). We have modelled the light curves obtained together with earlier reported fluxes from WSRT

(van der Horst *et al.* 2005), GMRT (Resmi *et al.* 2005) and VLA and ATCA (Berger *et al.* 2003; Frail *et al.* 2005). The afterglow was clearly detected at all frequencies except for 325 MHz, where we could only obtain upper limits ( $1\text{-}\sigma$  limits of approx. 0.5 mJy at roughly 2 years after the burst). GRB 030329 is the first afterglow to be detected at frequencies less than 1 GHz: at 840 MHz with WSRT and even as low as 610 MHz with GMRT.

The light curves show the peak of the broadband synchrotron spectrum moving to lower frequencies in time. After 80 days, the observed light curves decrease less steeply than expected, which can be explained by a transition into the non-relativistic phase of the blast wave (Resmi *et al.* 2005; Frail *et al.* 2005; van der Horst *et al.* 2005). It was suggested in van der Horst *et al.* (2005) that this late-time behaviour could also be explained by a third jet component with an even wider opening angle than the first two. However, the latter model is excluded by the observations less than 1 GHz, which leaves the model with the non-relativistic phase after 80 days as the preferred model for the late-time behaviour of the blast wave. The precise value of the time of the transition into the non-relativistic phase varies between 40 and 80 days for the different modelling methods applied in Resmi *et al.* (2005), Frail *et al.* (2005) and van der Horst *et al.* (2005).

Our modelling method also allows us to calculate the source size and its evolution (van der Horst & Wijers in preparation), and from that derive the scintillation properties of this afterglow. Scintillation due to the local interstellar medium modulates the radio flux of the afterglow, as can be seen in figure 1. van der Horst *et al.* (2005) suggested that the early (approx. 1.5 days) peak that seems to be present in the radio light curves could be the signature of the narrow jet component causing the early optical and X-ray light curves. They concluded that interstellar scintillation could be a second and better explanation, owing to the modelling constraints of the narrow jet component from the optical and X-ray observations. However, our calculations of the source size and the expected scintillation cannot account for the observed fluxes at early times. Resmi *et al.* (2005) pointed out that the deceleration of the wide jet component is expected to be accompanied by a radio flash from the reverse shock, as was also predicted by Piran *et al.* (2004). This could be the explanation for the observed fluxes.

#### 4. Low-Frequency Array

The Low-Frequency Array (LOFAR) will be a major new multi-element, interferometric, imaging telescope designed for the 30–240 MHz frequency range. LOFAR will use an array of simple omnidirectional antennas. The electronic signals from the antennas are digitized, transported to a central digital processor and combined in software to emulate a conventional antenna. LOFAR will have unprecedented sensitivity and resolution at metre wavelengths. This will give the GRB community the opportunity to study bright afterglows on even longer time-scales than with observations at centimetre wavelengths.

We have extrapolated the modelling results of the radio afterglow of GRB 030329 to the LOFAR observing range (van der Horst *et al.* in preparation) (figure 2). The predicted light curves show that GRB 030329 will be observable in the high band of LOFAR (120–240 MHz), but not in the low band (30–80 MHz). The light curves are expected to peak in 2009, when LOFAR will be fully

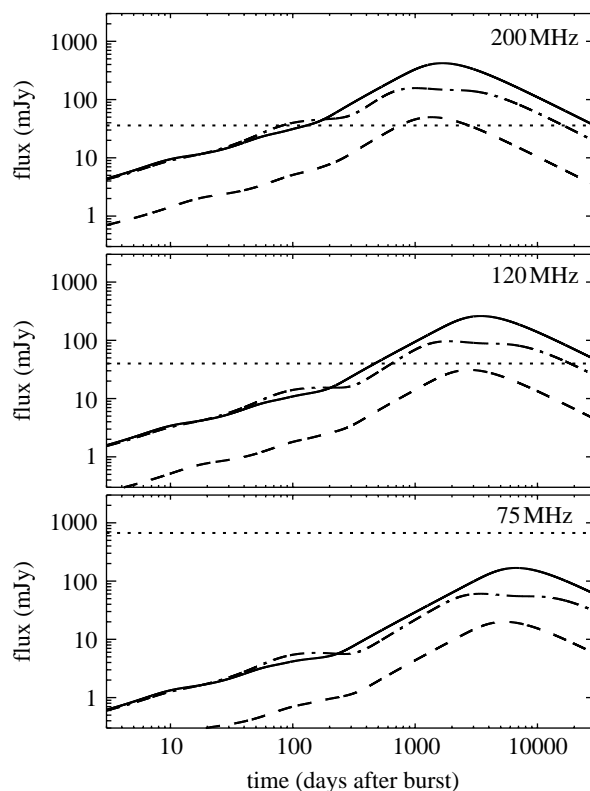


Figure 2. The predicted light curves of GRB 030329 at three frequencies within the LOFAR observing range. The solid and dash-dotted lines correspond to the two models shown in figure 1; the dashed line shows the predicted light curve of GRB 030329 when situated at a redshift of 1 instead of 0.16. The horizontal dotted lines are the sensitivity limits after 4 h of observing. It shows that GRB afterglows similar in brightness to that of GRB 030329 can easily be detected with LOFAR on time-scales of months to decades; and that the fainter afterglows can also be detected after long integration times.

operational, and even later going down from 240 to 120 MHz. We also calculated light curves for GRB 030329 if it were situated at a redshift of 1 instead of 0.16. The resulting fainter afterglow can also be detected, although with longer integration times, i.e. on the order of a day instead of an hour.

We greatly appreciate the support from the WSRT and GMRT staff in their help with scheduling these observations. The Westerbork Synthesis Radio Telescope is operated by the ASTRON (Netherlands Foundation for Research in Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO). The Giant Metrewave Radio Telescope is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

## References

- Berger, E. *et al.* 2003 A common origin for cosmic explosions inferred from calorimetry of GRB030329. *Nature* **426**, 154–157. ([doi:10.1038/nature01998](https://doi.org/10.1038/nature01998))
- Frail, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M. & Taylor, G. B. 1997 The radio afterglow from the  $\gamma$ -ray burst of 8 May 1997. *Nature* **389**, 261–263. ([doi:10.1038/38451](https://doi.org/10.1038/38451))

- Frail, D. A., Soderberg, A. M., Kulkarni, S. R., Berger, E., Yost, S. A., Fox, D. W. & Harrison, F. A. 2005 Accurate Calorimetry of GRB 030329. *Astrophys. J.* **619**, 994–998. (doi:10.1086/426680)
- Hjorth, J. *et al.* 2003 A very energetic supernova associated with the gamma-ray burst of 29 March 2003. *Nature* **423**, 847–850. (doi:10.1038/nature01750)
- Piran, T., Nakar, E. & Granot, J. 2004 *AIP Conf. Proc.* **727**, 181–186. (doi:10.1063/1.1810827)
- Resmi, L. *et al.* 2005 Radio, millimeter and optical monitoring of GRB 030329 afterglow: constraining the double jet model. *Astron. Astrophys.* **440**, 477–485. (doi:10.1051/0004-6361:20041642)
- Stanek, K. Z. *et al.* 2003 Spectroscopic discovery of the supernova 2003dh associated with GRB 030329. *Astrophys. J.* **591**, L17–L20. (doi:10.1086/376976)
- Tiengo, A. *et al.* 2004 Late evolution of the X-ray afterglow of GRB 030329. *Astron. Astrophys.* **423**, 861–865. (doi:10.1051/0004-6361:20041027)
- van der Horst, A. J. *et al.* 2005 The radio afterglow of GRB 030329 at centimeter wavelengths: evidence for a structured jet or non-relativistic expansion. *Astrophys. J.* **634**, 1166–1172. (doi:10.1086/497021)
- van der Horst A. J. *et al.* In preparation.
- van der Horst A. J. & Wijers R. A. M. J. In preparation.
- Wijers, R. A. M. J. & Galama, T. J. 1999 *Astrophys. J.* **523**, 177–186. (doi:10.1086/307705)