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The Rapidly Fading Afterglow from the Gamma-Ray Burst of 1999 May 6[1]

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ABSTRACT

We report on the discovery of the radio afterglow from the gamma-ray burst (GRB) of 1999 May 6 (GRB 990506) using the Very Large Array (VLA). The radio afterglow was detected at early times ($\Delta t = 1.5$ days), but began to fade rapidly sometime between 1 and 5 days after the burst. If we attribute the radio emission to the forward shock from an expanding fireball, then this rapid onset of the decay in the radio predicts that the corresponding optical transient began to decay between 1 and 5 minutes after the burst. This could explain why no optical transient for GRB 990506 was detected in spite of numerous searches. The cause of the unusually rapid onset of the decay for the afterglow is probably the result of an isotropically energetic fireball expanding into a low density circumburst environment. At the location of the radio afterglow we find a faint ($R \sim 24$ mag) host galaxy with a double morphology.

Subject headings: gamma rays:bursts – radio continuum:general – cosmology:observations

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1. Introduction

GRB 990506 was detected by the BATSE (trigger No. 7549) on board the Compton Gamma-Ray Observatory (CGRO) on 1999 May 6.47 UT (Kippen 1999). It was a bright burst, lasting approximately 150 s, with a fluence in the 50-300 keV band of 2.23×10^{-4} erg cm^{-2} – placing it in the top 2% of BATSE bursts as ranked by fluence. The PCA instrument on board the Rossi X-Ray Timing Explorer (RXTE) began scanning a $8^\circ \times 6^\circ$ region centered on the BATSE position some three hours after the burst (Marshall & Takeshima 1999) and discovered a previously uncataloged X-ray source, which faded significantly over the observing interval (Takeshima & Marshall 1999). The initial $12'$ error circle for the RXTE-PCA position of GRB 990506 was further refined to a 30 arcmin^2 region through the addition of timing annuli from the Interplanetary Network (IPN), involving the NEAR, Ulysses and CGRO satellites (Hurley *et al.* 1999).

Despite the fact that at least nine different optical telescopes imaged the IPN/RXTE-PCA region containing the X-ray transient (some as early as 90 minutes after the burst), no corresponding optical transient was detected. In this paper we report the discovery of a radio transient (VLA J115450.1−2640.6) in this field, which we propose is the radio afterglow of GRB 990506. We also present upper limits on the brightness of the corresponding optical afterglow. We discuss the radio light curve of this transient, and its implications for the lack of detection of the optical afterglow. Finally, we present the discovery of the probable host galaxy of the radio transient, and by implication the GRB itself. GRB 990506 joins a small but growing class of bursts which evidently lack a bright optical transient but are seen at both X-ray and radio wavelengths.

2. Discovery of the Radio Afterglow

Very Large Array (VLA) observations were initiated 1.5 days after the γ-ray burst. Details of this and all subsequent VLA observations are given in Table 1. In order to image the entire $11.5'\times2.5'$ error region with the VLA at 8.46 GHz two pointings were required, each with a field-of-view at half power response of $5.3'$ in diameter. In the southern field we detect two sources whose flux density ($\sim$ 150 μJy) did not vary significantly from 1999 May 8 to 1999 May 21. There were two additional sources in the northern pointing, only one of which was within the IPN/RXTE-PCA error box. This source, hereafter VLA J115450.1−2640.6, was clearly detected during the first two epochs but had faded by at least a factor of three thirteen days later. VLA J115450.1−2640.6 was located at (epoch J2000) $\alpha = 11^h54^m50.13^s$ ($\pm0.02^s$) $\delta = -26^\circ40'35.0''$ ($\pm0.4''$), where the errors are the quoted 1σ uncertainties in the Gaussian fit obtained from the combined images on May

8 and May 9. The source has not been detected since at any frequency (see Fig. 1). A search was made for polarized emission by imaging the combined datasets on May 8 and 9 in all four Stokes parameters. The 3σ upper limits were 30% for both linear and circular polarization.

Of immediate concern is the possibility that VLA J115450.1−2640.6 is a background variable radio source lying by chance within the moderately large IPN/RXTE-PCA error box. On the basis of the radio data alone we cannot eliminate this possibility altogether. However, the order of magnitude change in source strength over the two weeks immediately following the GRB, and the failure to detect any subsequent radio emission after monitoring for 375 days, strongly suggests that VLA J115450.1−2640.6 was the afterglow of GRB 990506. We now proceed with this hypothesis.

Reaching a flux density of 580 μJy, GRB 990506 is in the top half of the dozen radio radio afterglows detected to date (ranked by flux density), fainter only than GRB 970508, GRB 980703, GRB 991208, and GRB 991216. There is some indication that the flux density increased from Δt=1.66 to 2.70 days (see Table 1) but the change in flux ΔS=134±68 μJy is only marginally significant. Some time between 2.5 days after the burst and 15.5 days, the radio afterglow declined below a detectable level. If we describe this decline in flux density, F_R, as a power-law in time (*i.e.,* $F_R \propto t^{\alpha_d}$) then the minimum slope of the decline depends on the poorly determined time, t_m, for the onset of the decline such that $\alpha_d^{-1} \simeq \log t_m - \log\ 15.66$.

3. Limits on the Optical Afterglow, and Discovery of the Host Galaxy

We obtained our first optical image of the field of GRB 990506 using the 60-inch CCD Camera (160 arcmin^2 field of view) approximately 18 hr after the GRB and continued for the next four nights. More details of the R-band optical observations to date are presented in Table 2. No confirmed optically variable sources in the IPN error box were found by our group and others (*e.g.,* Henden *et al.* 1999, Pedersen *et al.* 1999a).

At the position of the radio transient, an upper limit as strict as $R \gtrsim 23.5$ (Pedersen *et al.* 1999b) is placed on the brightness of any point-source optical afterglow starting 12 hours after the burst. Table 2 summarizes the R-band optical limits; our V-band observations on the first fours days also revealed no counterpart to less stringent flux densities.

On 11 June 1999 UT, 35.78 days after the GRB, we re-observed the field of GRB 990506 at the position of the radio transient using the Low Resolution Imaging Spectrometer (LRIS; Oke *et al.* 1995) on the Keck II 10-meter Telescope on Mauna Kea, Hawaii. Six images of the field totaling 26 minutes of integration were obtained in the Cousins R-band. Observations of the standard field PG 1323-086 (Landolt 1992) were used for magnitude zero-point calibration, which we also checked against the photometry by Vrba *et al.* (1999). An astrometric plate solution was obtained relative to the USNO A2.0 catalog (Monet *et al.* 1998) with a statistical error of 0.24, 0.27 arcsec (α, δ).

Figure 2 depicts the position of the radio transient and persistent 1.4 GHz emission overlaid atop the optical Keck image. Coincident with the position of the fading radio source is a faint extended (NE-SW) galaxy with an irregular morphology. The putative host appears as two knots of roughly equal brightness, with the radio transient position lying within the southwest knot. We find $R = 24.0 \pm 0.3$ and $R = 24.4 \pm 0.3$ mag for the northeast and southwest knots, respectively, based on photometry from the USNO (Vrba *et al.* 1999). The error in these magnitudes reflects the uncertainty in the color of the galaxy and aperture correction. The morphology of the host is suggestive of a merging or interacting galaxy pair.

4. Field radio Galaxies

In a deep radio image taken at 1.4 GHz on 1999 June 12, two weak background radio sources are seen within 30″ of VLA J115450.1−2640.6 (Fig. 2). The stronger of the two sources (R1) is 23″ to the SE and has a flux density of 540 μJy at 1.4 GHz. This source is undetected at 8.46 GHz, requiring either that it is resolved out at higher resolution or that it has a moderately steep spectral index, $\alpha < -1.1$, where $S \propto \nu^{\alpha}$. The weaker of the two nearby sources (R2) is detected some 30″ to the NW of VLA J115450.1−2640.6. This source has a flux density of 170 μJy at 1.4 GHz and a spectral index steeper than -0.5. From recent spectroscopic observations (see table 2) we identify the two radio sources (R1 and R2) with an early-type spiral and a QSO at redshifts $z = 0.326$ and $z = 0.273$, respectively.

5. Discussion

The simplest explanation for the behavior of the radio afterglow from GRB 990506 is that the emission originates in the forward shock driven into the surrounding medium by the relativistically expanding blast wave (Sari, Piran & Narayan 1998). In this case the apparent rise in the 8.46 GHz light curve to a maximum F_m, followed by a decay is the result of an evolving synchrotron spectrum, produced from electrons accelerated in the shock, whose peak frequency ν_m passed through the band during our observing interval. As noted in §2, the exact time, t_m, for the onset of the decay and the value of the power-law slope, α_d, are uncertain owing to the undersampling of the light curve. Given the data, a range of t_m values from 1 to 5 days are possible. The upper limit on t_m is determined by requiring that $\alpha_d > -2$. Significantly steeper values have yet to be seen for other afterglows. Furthermore, this value is entirely consistent with the X-ray decay $\alpha_d = -1.9 \pm 0.6$ for this burst as measured by the RXTE-ASM (Takeshima & Marshall 1999). For $1 \leq t_m \leq 5$ days the corresponding values of the decay slope are $-0.8 \leq \alpha_d \leq -2$.

In Figure 1 we plot a 8.46 GHz light curve expected for a adiabatic forward shock, propagating in a homogeneous medium to demonstrate that such models are consistent with the data. In this representative model, the peak flux is 580 μJy, t_m=2.5 days, and $\alpha_d = -1.25$. The tightest constraint on α_d and/or t_m comes from the 1.4 GHz flux density upper limit on 1999 June 12.92 UT. Reasonable model inputs predict peak flux densities at this frequency of order 100-200 μJy. Therefore, at least this one epoch favors the steeper decay indices and the smaller t_m values from the ranges given above.

The estimated t_m value suggests that GRB 990506 entered the decay phase at 8.46 GHz considerably earlier than previous radio afterglows. At this same frequency the decay timescales for GRB 970508 (Frail, Waxman & Kulkarni 2000), GRB 980329 (Frail *et al.* 2000a), GRB 980519 (Frail *et al.* 2000b), GRB 990510 (Harrison *et al.* 1999), GRB 981216 (Frail *et al.* 1999) range from 8.5 days to 90 days. Only GRB 990123 exhibited a faster decay (Kulkarni *et al.* 1999; see below).

One consequence of the early radio decay is that the apparent absence of the optical afterglow can now be understood rather simply without the need to invoke excess extinction along the line of sight. If the synchrotron peak moved through the radio band ν_R on the order of t_m=1-5 days, then the corresponding timescale for the peak to move through the optical bands ν_o is $t_o = t_m\,(\nu_R/\nu_o)^{2/3}$, or $60 \leq t_m \leq 300$ s (Mészáros & Rees 1997). This small timescale can be contrasted with GRB 971214 for which Ramaprakash *et al.* (1998) derived t_o=0.6 days at $\nu_m = 3 \times 10^{14}$ Hz. In general, the flux density decays from its peak F_m as a power law with index α_d for $t > t_o$. Provided that the synchrotron peak frequency F_m remains constant (as it should if dealing with a spherical, adiabatic expansion), then the peak 8.4 GHz flux density of 580 μJy predicts a peak optical afterglow emission of $R = 17$ mag (after correcting for foreground extinction). Even a relatively shallow decay, $\alpha_d = -1.25$, predicts that the OT was already undetectable at $R = 22$ mag 90 minutes after the burst when the field of GRB 990506 was observed by Zhu & Zhang (1999). By the time of the deep R-band observations (*e.g.,* Masetti *et al.* 1999, Pedersen *et al.* 1999b) the OT had $R \gtrsim 25$ mag and was likewise undetectable.

Perhaps more importantly, the early radio decay is indicative of unusual physical conditions. Short-lived but moderately bright afterglows can result if the GRB exploded with a high energy ($E_\circ$) into a low density medium ($n_\circ$), or, as noted by Galama *et al.* (1999), the magnetic field in the forward shock was weak. Unfortunately, while we have constrained F_m and $\nu_m(t_m)$, the paucity of broadband data for this burst does not allow us to determine other important observables such as the synchrotron self-absorption frequency ν_a and the cooling frequency ν_c. Without this information it is not possible to fully constrain the physical properties of the afterglow and the surrounding medium (Wijers & Galama 1999).

Alternatively, prompt radio emission, analogous to the well-known optical emission (Akerlof *et al.* 1999), was also seen in the afterglow from GRB 990123 (Kulkarni *et al.* 1999) and perhaps GRB 970828 as well. This radio emission arises in the reverse shock in the days following a γ-ray burst (Sari & Piran 1999). It is suppressed at early times by synchrotron self-absorption, while at later times the light curve decays rapidly ($\propto t^{-2}$).

We note that it is possible that the southwest knot may itself be the optical transient since the GRB field has not been reimaged since 35 days after the burst. However, even a shallow decay in the optical of t^{-1} then predicts an R-band magnitude of 20.1 one day after the burst which was not observed. We thus find it unlikely that the southwest knot could be an optical transient given the early non-detections. Instead, we interpret the two knots as part of the host galaxy of GRB 990506. The apparent R-band magnitude of the putative host of GRB 990506 is similar to that of other GRB host galaxies. Spectroscopic observations are necessary in order to establish the redshift and other physical properties of this host galaxy. The bimodal morphology may be indicative of merger activity. In this respect the host appears similar to a growing number of GRB hosts with irregular morphology: GRB 980613 (Djorgovski *et al.* 1999), GRB 970828 (Djorgovski *et al.* 2000), and GRB 990123 (Bloom *et al.* 1999).

6. Conclusions

We have identified the radio afterglow from GRB 990506. This GRB was unusual in that it produced a radio afterglow that began to fade at very early times (between 1 and 5 days after the burst) and in that no optical afterglow was detected in spite of the numerous deep images obtained. Both these observations may be explained by a high energy spherical fireball expanding into a low density environment. In this simple picture there is no need to invoke dust extinction to account for the lack of detection of an optical afterglow. We cannot rule out, however, that the radio emission originated in a reverse shock. If the reverse shock produced the radio afterglow, then the emission from the forward shock (in both optical and radio) was presumably too faint to be seen. To find additional GRBs of this type will require more rapid followup to precise burst localizations than has typically been achievable. Upcoming satellite missions such as HETE II and SWIFT should improve upon this situation.

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Table 1. VLA Observations of GRB 990506

Epoch (UT)	Δt (days)	Freq. (GHz)	$F_R \pm \sigma$ (μJy)	98% confidence (μJy)
1999 May 8.13	1.66	8.46	447±50	
1999 May 9.17	2.70	8.46	581±45	
1999 May 22.13	15.66	8.46	55±41	<139
1999 Jun. 6.09	30.62	4.86	−46±80	<164
1999 Jun. 7.96	32.49	1.40	−21±90	<185
1999 Jun. 8.03	32.56	8.46	41±36	<115
1999 Jun. 12.99	37.52	8.46	8±31	<72
1999 Jun. 13.00	37.53	1.40	−80±33	<68
1999 Aug. 6.03	91.56	1.40	1±60	<124
1999 Aug. 22.82	108.35	8.46	25±30	<87
1999 Sep. 24.70	141.23	8.46	37±25	<88
2000 Jan. 5.50	244.03	8.46	−54±70	<144
2000 May. 16.16	375.69	8.46	−5±33	<68

Note. — The columns are (left to right), (1) UT date of the start of each observation; (2) Time elapsed since the γ-ray burst; (3) The observing frequency; (4) The peak flux density at the best fit position of the radio transient, with the error given as the root mean square (rms) flux density in the off-source region of the image; and (5) The 98% confidence upper limit computed from the measured value in (4) if greater than 0 plus 2.05 times the rms. Observations employed a bandwidth of 100 MHz and all four Stokes parameters were recorded. The instrumental phase was calibrated with J1146−247 and J1145−228 and the flux scale was tied to J1331+305.

Table 2: Optical Imaging and Spectroscopic Observations of GRB 990506

Date UT	Inst.[a]	Int. Time (sec)	Δt (days)	R Mag[b] observed	Reference
1999 May 6.53	BAO	300	0.058	$\gtrsim 19.0$	Zhu & Zhang 1999
1999 May 6.96	NOT	480	0.486	$\gtrsim 23.5$	Pedersen *et al.* 1999b
1999 May 7.228	P60	1920	0.754	$\gtrsim 22.1$	this paper
1999 May 7.565	ESO	1800	1.019	$\gtrsim 23.0^c$	Masetti *et al.* 1999
1999 May 8.231	P60	1920	1.757	$\gtrsim 22.5$	this paper
1999 May 8.284	P200	600	1.81	$\gtrsim 22.6$	this paper
1999 May 9.226	P60	1920	2.752	$\gtrsim 20.9$	this paper
1999 Jun 11.25	LRIS	1500	35.78	24.4 ± 0.3	this paper
2000 Feb 14.49	ESI	5400	285.02	...	this paper

[a] Instruments: BAO = 0.6/0.9m Schmidt telescope in Xinglong; NOT = The ALFOSC on the 2.56-m Nordic Optical Telescope; P60 = CCD Camera on the 60-inch Palomar Telescope; P200 = COSMIC Reimaging on the 200-inch Hale Telescope, Palomar; LRIS = Low-Resolution Spectrometer on 10-m Keck II, Mauna Kea. ESI = Echellete Spesctrograph and Imager on the Keck II 10-m.

[b] Upper limits are 3σ for a point-source detection at the position of the radio afterglow unless otherwise noted.

[c] This value is a 3σ upper limit to variability in the IPN localization greater than $R = 0.3$ mag as compared to later epochs.

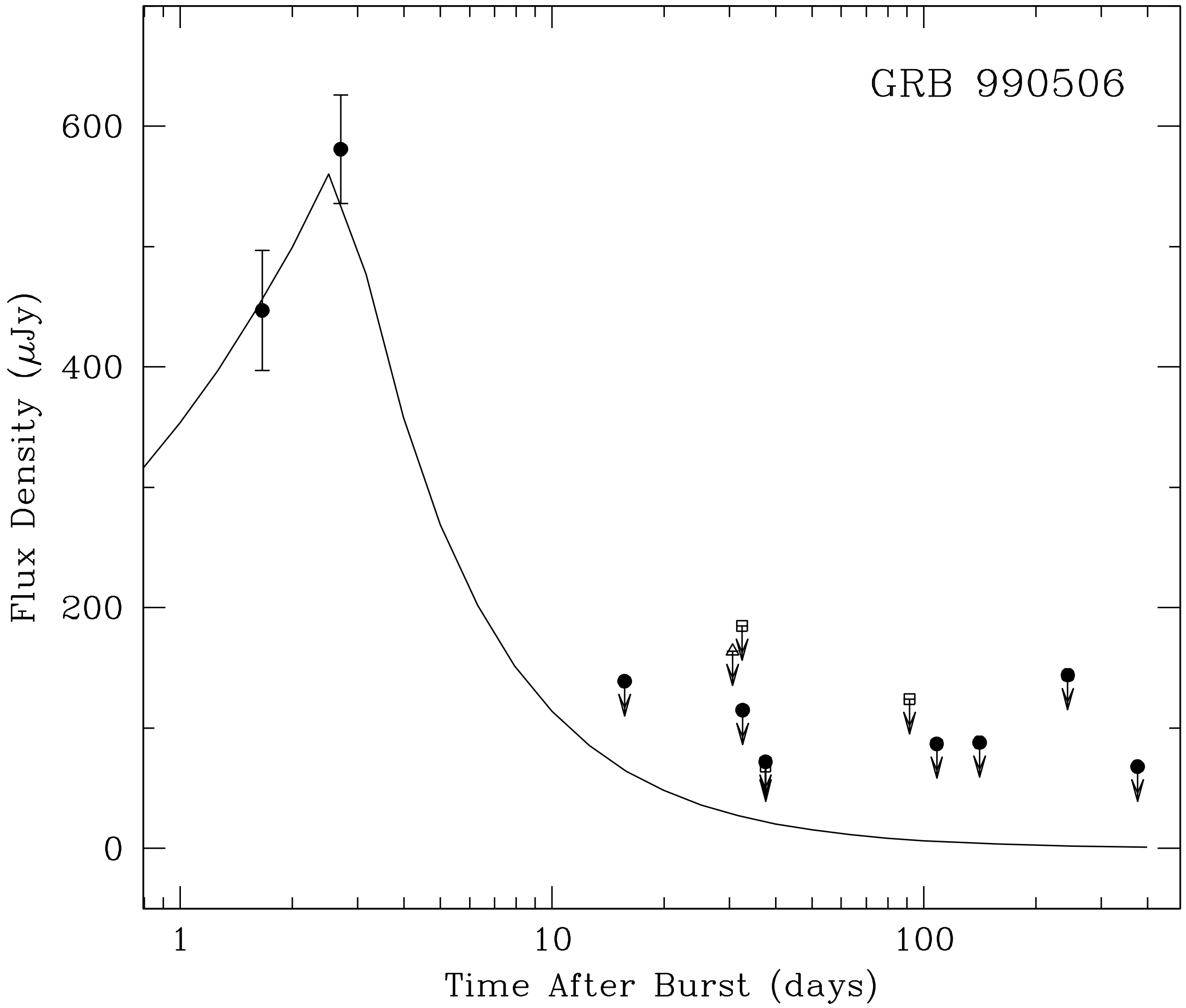

Fig. 1.— The radio light curve for VLA J115450.1−2640.6. Key to symbols: filled circles are 8.46 GHz observations; open squares are 1.4 GHz observations and the open triangle represents a single observation at 4.86 GHz. Upper limits are ploted as the flux density at the position of VLA J115450.1−2640.6 (if positive) plus 2.05 times the rms noise (see Table 1). The solid line is the expected emission at 8.46 GHz for a forward shock propagating into a constant density medium. The light curve rises as $t^{1/2}$ until t_m=2.5 days, and thereafter decays with $\alpha_d = -1.25$ (*i.e.*, t^{α_d}). The model is meant to be representative only. There is a range t_m and α_d, allowed by these data (see text for details).

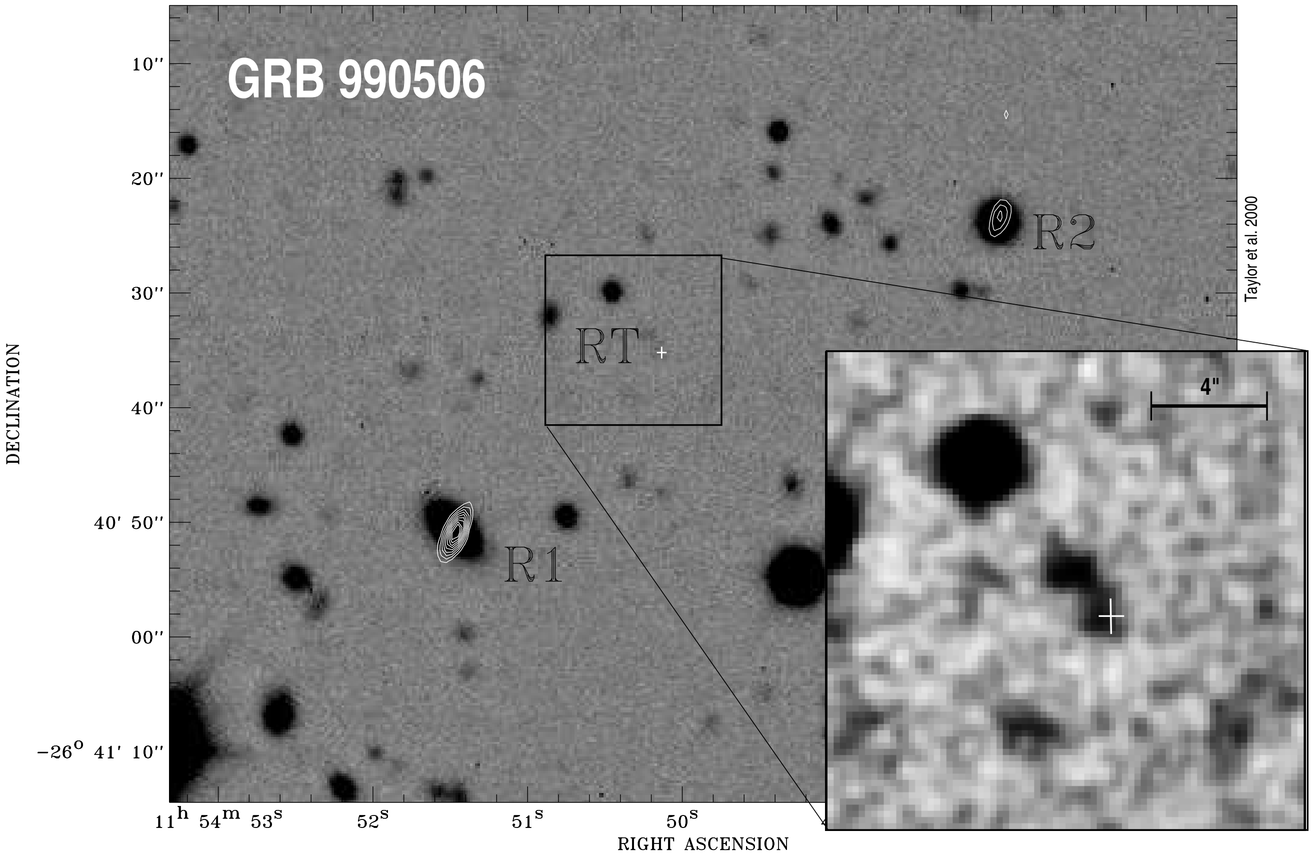

Fig. 2.— The optical field of GRB 990506 with radio overlay. The optical image a sum of 1500 s from Keck taken 35 days after the GRB. The radio contours (white) are in incremental units of r.m.s. noise (2–10 σ) at an observing frequency of 1.4 GHz. The cross shows the relative 2-σ position of the transient radio source associated with GRB 990506. Added in quadrature to the radio transient positional uncertainty are the r.m.s. statistical uncertainty of the optical tie to the USNO A2.0 catalogue (see text) and the systematic error in the tie of USNO A2.0 and the International Coordinate Reference frame (Deutsch 1999). The radio transient is coincident with the south-western knot of a faint galaxy, whose bimodal morphology is suggestive of an interacting system.