# The Host Galaxy of GRB 990123

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## ABSTRACT

We present deep images of the field of $\gamma$-ray burst (GRB) 990123 obtained in a broad-band UV/visible bandpass with the Hubble Space Telescope, and deep near-infrared images obtained with the Keck-I 10-m telescope. Both the HST and Keck images show that the optical transient (OT) is clearly offset by 0.6 arcsec from an extended object, presumably the host galaxy. This galaxy is the most likely source of the metallic-line absorption at $z = 1.6004$ seen in the spectrum of the OT. With magnitudes $V_C \approx 24.6 \pm 0.2$ and $K = 21.65 \pm 0.30$ mag this corresponds to an $L \sim 0.7\, L_*$ galaxy, assuming that it is located at $z = 1.6$. The estimated unobscured star formation rate is $SFR \sim 6\ M_\odot$ yr$^{-1}$, which is not unusually high for normal galaxies at comparable redshifts. The strength of the observed metallic absorption lines is suggestive of a relatively high metallicity of the gas, and thus of a chemically evolved system which may be associated with a massive galaxy. It is also indicative of a high column density of the gas, typical of damped Ly$\alpha$ systems at high redshifts. We conclude that this is the host galaxy of GRB 990123. No other obvious galaxies are detected within the same projected radius from the OT. There is thus no evidence for strong gravitational lensing magnification of this burst, and some alternative explanation for its remarkable energetics may be required. The observed offset of the OT from the center of its apparent host galaxy, $5.5 \pm 0.9$ proper kpc (projected) in the galaxy's rest-frame, both refutes the possibility that GRBs are related to galactic nuclear activity and supports models of GRBs which involve the death and/or merger of massive stars. Further, the HST image suggests an intimate connection of GRB 990123 and a star-forming region.

*Subject headings:* cosmology: miscellaneous — cosmology: observations — gamma rays: bursts

## 1. Introduction

A great deal of progress has been achieved in our understanding of cosmic $\gamma$–ray bursts (GRBs) over the past two years. The breakthrough development was the precise localization of bursts by the BeppoSAX satellite (Boella *et al.* 1997), which led to the discovery of long-lived afterglows of GRBs, ranging from x-rays (Costa *et al.* 1997), to optical (van Paradijs *et al.* 1997) and radio (Frail *et al.* 1997). This, in turn, has opened the possibility of detailed physical studies of the afterglows, and measurements of their distances.

To date, several optical transients (OTs) associated with GRBs have been found, and in almost every case a faint galaxy was found at the same location (to within a fraction of an arcsecond) after the OT has faded. So far, redshifts have been obtained for four such GRB host galaxies: $z = 0.835$ for GRB 970508 (Metzger *et al.* 1997, Bloom *et al.* 1998), $z = 3.428$ for GRB 971214 (Kulkarni *et al.* 1998), $z = 0.966$ for GRB 980703 (Djorgovski *et al.* 1998), and $z = 1.0964$ for GRB 980613 (Djorgovski *et al.* 1999a). These measurements have established that most or all GRBs are located at cosmological distances (Paczyǹski 1995), involving substantial energy release (isotropic equivalent $E \gtrsim 10^{52\pm1}$ in the $\gamma$-rays alone).

While the ultimate origin of GRBs is still not established, studies of their afterglows provide several crucial constraints for theoretical models. First, the measurement of distances establishes the energetics of the bursts, modulo the unknown beaming factor. Second, detailed studies of the afterglow light curves over a range of wavelengths can constrain the physical parameters of the afterglows, including the energetics and beaming. Finally, the location of the afterglows within their host galaxies and measurements of the star formation rates (SFR) in these galaxies can constrain the nature of the population of GRB progenitors.

The two leading models for GRBs involve the formation of a black hole (BH): either via coalescence of a massive stellar remnant binary (eg. BH–NS, NS–NS; Paczyǹski 1986,Goodman 1986,Narayan, Paczyǹski, & Piran) or direct collapse of a massive star (Woosley 1993, Paczyǹski 1998). Both models predict that GRBs rates should strongly correlate with the cosmic star-formation rates (SFR) and so most GRBs should occur in the redshift range $z = 1 - 2$. The former model predicts a tight spatial correlation between GRBs and star-forming regions in the disk. In the latter scenario, however, the coalescence site of a NS–NS binary can be quite distant ($\gtrsim$ few kpc) from the stellar birth site (see Bloom, Sigurdsson, & Pols 1999). GRBs could also be associated with nuclear black holes (AGN); see Roland *et al.* 1994. In this scenario, unlike either model described above, the GRBs will occur in the center of the host.

Until recently, the most spectacular example of GRB energetics was seen with GRB 971214 at $z = 3.418$ (Kulkarni *et al.* 1998): the implied isotropic energy released from the burst in the $\gamma$-rays alone was $E_\gamma \approx 3 \times 10^{53}$ erg, some two orders of magnitude higher than the commonly assumed numbers. However, this was further surpassed by an order of magnitude by the recent discovery of GRB 990123.

Following the detection by BeppoSAX (Piro *et al.* 1999), an optical transient was discovered at Palomar (Odewahn, Bloom, & Kulkarni 1999), and subsequently a coincident radio transient was found at the VLA (Frail & Kulkarni 1999), within the error-circles of the GRB itself and the associated new x-ray source (Piro *et al.* 1999). Examination of the ROTSE images taken within minutes of the burst revealed an unprecedented bright ($m_{peak} \approx 8.9$ mag) phase of the optical afterglow (Akerlof & McKay 1999). Spectroscopy of the OT obtained at the Keck-II 10-m telescope revealed an absorption system with $z_{abs} \approx 1.61$ (Kelson *et al.* 1999). Together with the GRO/BATSE measurement of the burst fluence (Kippen 1999), this implied a phenomenal energetics for the burst and its afterglow. The absorption redshift was subsequently confirmed independently by Hjorth *et al.* 1999a, and further refinement of the spectroscopy

improved the redshift measurement to $z_{abs} = 1.6004$ (Hjorth *et al.* 1999b, Djorgovski *et al.* 1999d). A fading infrared counterpart was discovered at the Keck-I 10-m telescope (Bloom *et al.* 1999b).

The early reports indicated a presence of an apparent foreground galaxy within $\sim 2$ arcsec from the OT (Odewahn, Bloom, & Kulkarni 1999, Bloom *et al.* 1999a, Gal *et al.* 1999) and, later found, the presence of foreground emission and absorption lines at $z = 0.210$ and $z = 0.286$ (Hjorth *et al.* 1999a). Motivated by these reports, and the unprecedented apparent energetics of the burst, it was proposed that this burst may have been gravitationally lensed (Djorgovski *et al.* 1999b). However, subsequent observations and analysis did not confirm the existence of this foreground galaxy (Yadigaroglu *et al.* 1999, Djorgovski *et al.* 1999c) nor low-redshift absorbers close to the line-of-sight (Hjorth *et al.* 1999b, Djorgovski *et al.* 1999d). Thus, the empirical motivation for the gravitational lensing of this burst was all but removed leaving open the problem of its energetics.

Kulkarni *et al.* 1999 present a detailed study of the ground-based work on this burst to date, and analyze its physical properties and energetics. Early ground-based observations are dominated by the afterglow light, which makes difficult the detection and study of the host galaxy (and possible foreground objects near the line of sight). In this *Letter* we report on the Hubble Space Telescope (HST) observations of the host galaxy of this burst, about 16 days after the burst itself, as well as the ground-based Keck imaging in the near-infrared, starting from about 6 days after the burst.

## 2. Observations and Data Reductions

The ground-based near-IR images of the field were obtained using the NIRC instrument (Matthews & Soifer 1994) at the Keck-I 10-m telescope. A log of the observations and a detailed description of the data and the reduction procedures are given by Kulkarni *et al.* 1999. The observations were obtained in the $K$ or $K_s$ bands, and were calibrated to the standard $K$ band ($\lambda_{eff} = 2.195$ $\mu$m). The Galactic extinction corrections are negligible in the $K$ band, assuming $E_{B-V} = 0.016$ in this direction (Schlegel, Finkbeiner, & Davis 1998).

The first evidence of the underlying galaxy, approximately 0.5 arcsec from the OT was seen in the Keck images taken on 27 January 1999 UT. We estimated a magnitude $K \sim 22$ mag (Djorgovski *et al.* 1999c). The galaxy, the putative host, which we designate as "A", was then clearly detected in the images obtained on 29 January 1999 UT (Djorgovski *et al.* 1999e), as shown in Figure 1. The total $K$-band magnitude of the OT plus the galaxy at that time (January 29.665 UT) was $K_{tot} = 20.30 \pm 0.10$ mag (including both random and systematic errors). We estimate the contribution of the galaxy to the total flux by masking the appropriate pixels of the transient, and find that the galaxy contributed about $21\% \pm 5\%$ of the total $K$-band light at that time, implying the magnitudes $K_{OT} = 20.56 \pm 0.17$ mag (at this epoch), and $K_{gal.\ A} = 22.0 \pm 0.4$ mag.

The total $K$-band magnitude measured on 9 February 1999 UT is $K_{tot} = 21.04 \pm 0.11$ mag. If the OT had a power-law spectrum $F_\nu \sim \nu^\beta$ with $\beta = -0.8$ and the extinction-corrected Gunn $r$-band flux at the same epoch $F_r = 0.263 \pm 0.055$ $\mu$Jy (Kulkarni *et al.* 1999), then the predicted $K$ band magnitude of the OT alone would be $K_{OT} = 22.41 \pm 0.21$ mag (at this epoch), and the resulting magnitude of the galaxy would be $K_{gal.\ A} = 21.40 \pm 0.20$ mag. However, the slope of the OT power-law continuum may have changed by that time, and if we assume $\beta = -1.0$ instead, we derive $K_{OT} = 22.14 \pm 0.21$ mag, and $K_{gal.A} = 21.53 \pm 0.23$ mag. We thus assume the estimate of $K_{gal.A} = 21.45 \pm 0.25$ mag from this decomposition.

Taking the weighted average of the two estimates, we find $K_{gal.A} = 21.65 \pm 0.30$ mag, corresponding to the flux $F_{\nu,K,gal.A} = 1.39 \pm 0.44$ $\mu$Jy. We assume for the flux zero-point of the $K$ band 636 Jy for $K = 0$ mag (Bessel & Brett 1988).

The HST observations of the GRB 990123 field were obtained on 8–9 February 1999 UT in response to the Director's Discretionary time proposal GO-8394, with the immediate data release to the general community. The CCD camera of the Space Telescope Imaging Spectrograph (STIS) (Kimble $et~al.$ 1998) in Clear Aperture (50CCD) mode was used. The CCD has a peak quantum efficiency at $\lambda = 5852$ Å over the wavelength range $\lambda 2000 - 10000$ Å. A total of 6 exposure of 1300 sec each was collected over 3 orbits. The field was imaged in six positions dithered in a spiral pattern. Each position was imaged twice to facilitate cosmic-ray removal (total of 12 integrations).

Initial data processing followed the STScI pipeline procedures, including bias and dark current subtraction. The six cosmic-ray removed images were then combined by registering the images and median stacking to produce a master science-grade image. Photometry and astrometry were performed with this image.

Figure 2 shows a portion of the STIS image of the GRB 990123 field. We find (see below) the OT as a point source clearly detected $0.648 \pm 0.1$ arcsec to the south of galaxy A. Galaxy A has an elongated and clumpy appearance, possibly indicative of star formation regions in a nearly edge-on (potentially late-type) disk galaxy, although a classification as a purely Irregular galaxy cannot be excluded. Such morphologies are typical for many galaxies at comparable flux levels, as observed with the HST. Its extension to the south clearly overlaps with the OT, and it is thus virtually certain that this galaxy is responsible for the absorption line system at $z_{abs} = 1.6004$ (Kelson $et~al.$ 1999, Kulkarni $et~al.$ 1999).

Our earlier ground-based imaging suggested the OT was displaced to the south of galaxy A, and we now confirm this with a precise astrometric tie between the discovery image and the STIS image. We measured the centroid of the optical transient in our discovery image from Jan 23 (Odewahn, Bloom, & Kulkarni 1999) at the Palomar 60-inch (P60). The OT was bright ($r = 18.65$) at this early epoch and its position is well-determined with respect to other objects in the field. Next we computed the astrometric mapping of the P60 coordinate system to a deep Keck II 10-m R-band image (see Kulkarni $et~al.$ 1999) using 75 well-centroided objects common to the two images. Similarly, we tie the Keck II coordinates to the STIS image using 19 common tie objects. We find the ground-based position of the OT is consistent with the STIS point-source with a negligible offset of $0.09 \pm 0.18$ arcsec.

The coordinates of the OT as measured in the HST image are $\alpha = 15^{\rm h}25^{\rm m}30^{\rm s}.3026$, $\delta = +44^{\rm d}45'59''.048$ (J2000). This is in an excellent agreement with an absolute astrometric measurement, tied to the USNO A-2.0 catalogue (Monet 98), from the ground-based image discussed in Bloom $et~al.$ 1999a. The coordinates of the center of galaxy "A" (extended North-South) are $\alpha = 15^{\rm h}25^{\rm m}30^{\rm s}.3175$, $\delta = +44^{\rm d}45'59''.676$ (J2000). The brightest knot connected with galaxy A is located at $\alpha = 15^{\rm h}25^{\rm m}30^{\rm s}.2835$, $\delta = +44^{\rm d}45'59''.576$ (J2000). The uncertainties in the relative positions are $\sim 10$ mas, but the positions in an absolute sense (relative to Hipparcos) are larger ($\sigma \simeq 0.3$ arcsec).

No other galaxies brighter than $V \sim 27$ mag are detected in the STIS image closer to the OT than galaxy A, and we see no evidence for a distant cluster (or even a sizable group) in this field. This effectively removes the possibility that the burst was significantly magnified by gravitational lensing.

We will assume for the Galactic reddening in this direction $E_{B-V} = 0.016$ mag (Schlegel, Finkbeiner, & Davis 1998), and use the standard Galactic extinction curve with $R = A_V/E_{B-V} = 3.1$ to estimate

extinction corrections at other wavelengths. We assume the photometric flux zero points as tabulated by Fukugita, Shimasaku, & Ichikawa 1995.

In order to convert the observed counts to fluxes and magnitudes, we use the web-based STIS exposure simulator (ETC). Since the bandpass of the STIS CLEAR is so broad, the conversion depends on the assumed spectrum of the object. For the OT, we can assume a power-law spectrum $F_\nu \sim \nu^\beta$ with $\beta = -0.8$ (Kulkarni *et al.* 1999). At the effective wavelength of the STIS bandpass, $\lambda_{eff} \approx 5850$ Å, for the OT alone we derive $F_{\nu,OT} = 0.308$ $\mu$Jy, uncertain by a few percent. Applying the Galactic extinction correction increases that number by about 5%. Assuming the same power-law, we derive the extinction-corrected magnitudes $V_{OT} = 25.17$ mag in the standard Johnson system, and $r_{OT} = 24.82$ mag in the Gunn-Thuan system.

For galaxy A, using the same power-law spectrum (which is a good approximation for star-forming galaxies with modest extinction, in this redshift range), we obtain $F_{\nu,gal.A} = 0.648$ $\mu$Jy, uncertain by a few percent, at $\lambda_{eff} \approx 5850$ Å, before the extinction correction. If we assume $\beta = 0$ instead (as it may be appropriate in the rest-frame UV for an actively star-forming galaxy and no extinction), we obtain $F_{\nu,gal.A} = 0.615$ $\mu$Jy. The difference is indicative of the net uncertainty of the flux conversion. We thus derive for the galaxy alone, in the $\beta = -0.8$ case: $V_{OT} = 24.36$ mag, $r_{OT} = 24.01$ mag, and the flux at $\lambda_{obs} = 7280$ Å, corresponding to $\lambda_{rest} = 2800$ Å, $F_{\nu,2800} = 0.798$ $\mu$Jy (all corrected for the Galactic extinction). If we assume $\beta = 0$, these values become: $V_{OT} = 24.37$ mag, $r_{OT} = 24.17$ mag, and $F_{\nu,2800} = 0.637$ $\mu$Jy.

We note that the simple power-law approximation to the broad-band spectrum of the galaxy, as defined by our STIS and $K$-band measurements, is $\beta_{gal.A} = -0.65 \pm 0.1$. This relatively blue color is suggestive of active star formation, but it cannot be used to estimate the SFR directly.

## 3. Discussion

We will assume a standard Friedman model cosmology with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.2$, and $\Lambda_0 = 0$. For $z = 1.6004$, the luminosity distance is $3.7 \times 10^{28}$ cm, and 1 arcsec corresponds to 8.64 proper kpc or 22.45 comoving kpc in projection.

It is practically certain that the absorption system at $z_{abs} = 1.6004$ originates from galaxy A, as no other viable candidate is seen in the HST images. The proximity of the center of galaxy A to the OT line of sight ($0.638 \pm 0.1$ arcsec), corresponding to 5.5 proper kpc at this redshift, strongly suggests that the two are physically related, and we propose that A is the host galaxy of the GRB. Visual inspection of Figure 2 suggests that a probability of chance superposition on this magnitude level is negligibly small.

In order to estimate the rest-frame luminosity of galaxy A, we interpolate between the observed STIS and $K$-band data points using a power-law, to estimate the observed flux at $\lambda_{obs} \approx 11570$ Å, corresponding approximately to the effective wavelength of the rest-frame $B$ band. We obtain $F_{\nu,B,rest} \approx 1.03$ $\mu$Jy, corresponding to the absolute magnitude $M_B = -20.4$. At $z \sim 0$, assuming $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, an $L_*$ galaxy has $M_B \approx -20.75$. We thus conclude that this object has the rest-frame luminosity $L \approx 0.7$ $L_{*,now}$. Given the uncertainty of the possible evolutionary histories, it may evolve to become either a normal spiral galaxy, or a borderline dwarf galaxy.

We can make a rough estimate of the SFR from the continuum luminosity at $\lambda_{rest} = 2800$ Å, following Madau *et al.* 1998. Using the $F_{\nu,2800}$ estimates given above, the corresponding monochromatic rest-frame

power is $P_{\nu,2800} = 4.21 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ (for $\beta = 0$, as it may be appropriate in the UV continuum itself), or $P_{\nu,2800} = 5.28 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ (for $\beta = -0.8$). The corresponding estimated unobscured star formation rates are $SFR \approx 5.3$ $M_\odot$ yr$^{-1}$ and $SFR \approx 6.7$ $M_\odot$ yr$^{-1}$, probably accurate to within 50% or better. This is a relatively modest value, but it may be typical for normal galaxies at such redshifts. It is of course a lower limit, as it does not include any extinction corrections in the galaxy itself, or any fully obscured star formation.

Further insight into the physical properties of this galaxy comes from its absorption spectrum, presented in Kulkarni *et al.* 1999. The lines are unusually strong, placing this absorber in the top 10% of all Mg II absorbers detected in complete surveys (Steidel & Sargent 1992). Unfortunately, without a direct measurement of the hydrogen column density, it is impossible to estimate the metallicity of the gas. However, the data suggest that the gas originated in a chemically evolved, massive galaxy. We note that strong metallic line absorbers are frequently associated with high hydrogen column density systems, such as damped Ly$\alpha$ absorbers. The scatter in the redshift measurements of the individual lines implies a very small velocity dispersion, less than 60 km s$^{-1}$ in the galaxy's rest-frame (Djorgovski *et al.* 1999d), implying that the absorber is associated either with a dwarf galaxy, or a dynamically cold disk of a more massive system, a possibility which we consider to be more likely.

It is worth examining the observed offset between the OT and the galaxy's center, in the context of previously studied cases. At least five GRBs now have offsets between the centroid of the visible host and the OT measured with sufficient accuracy to test association with galactic nuclei. Figure 3 shows the measured offset between the centroid of the host galaxy and the OT as a function of the host galaxy magnitude. Two of these offsets are based on previous STIS observations with HST: GRB 970228 by Fruchter *et al.* 1998 and GRB 971214 by Odewahn *et al.* 1998. The host magnitude is correlated with galaxy radius, and we use it as an objective measure of the host size. The two curves in Fig. 3 represent the median trend in effective radius ($\sim$ half-light radius) as a function of apparent magnitude. Smooth relations were computed with overlapping magnitude bins using approximately 1304 faint galaxies measured in F814W and F606W in two deep WFPC2 fields by Odewahn *et al.* 1996. Applying these mean trends to the total magnitude of all known host galaxies to date we note that the optical transients (except for 990123) lie well within the effective radius predicted for each host.

While the offset of the OT with respect to the effective radius (as inferred from observed magnitude) is a useful estimate of the relation of the GRB to the host, resolved imaging using HST provides the clearest picture. The transient of GRB 970228 is clearly displaced from its host center, but within the effective radius. GRB 970508, on the other hand, is coincident with the nucleus of its host galaxy to 0.01 arcseconds. Lastly, GRB 990123 is clearly separated from the central region of host and appears to be coincident with a star-forming region (see Fig. 2).

It has been clear since the discovery of GRB optical transients that GRBs are connected with galaxies. Gradually, however, a more specific picture has emerged. Imaging of the transient of GRB 990123 and its host is perhaps the best direct observational evidence that GRBs are intimately connected with the formation of stars: GRBs are clearly not a nuclear phenomenon, nor do most occur far-outside their host. The present suggestion of the spatial coincidence of GRB 990123 with a star-formation regions opens the possibility of studying not just GRBs in galaxies, but GRBs in their host environments.

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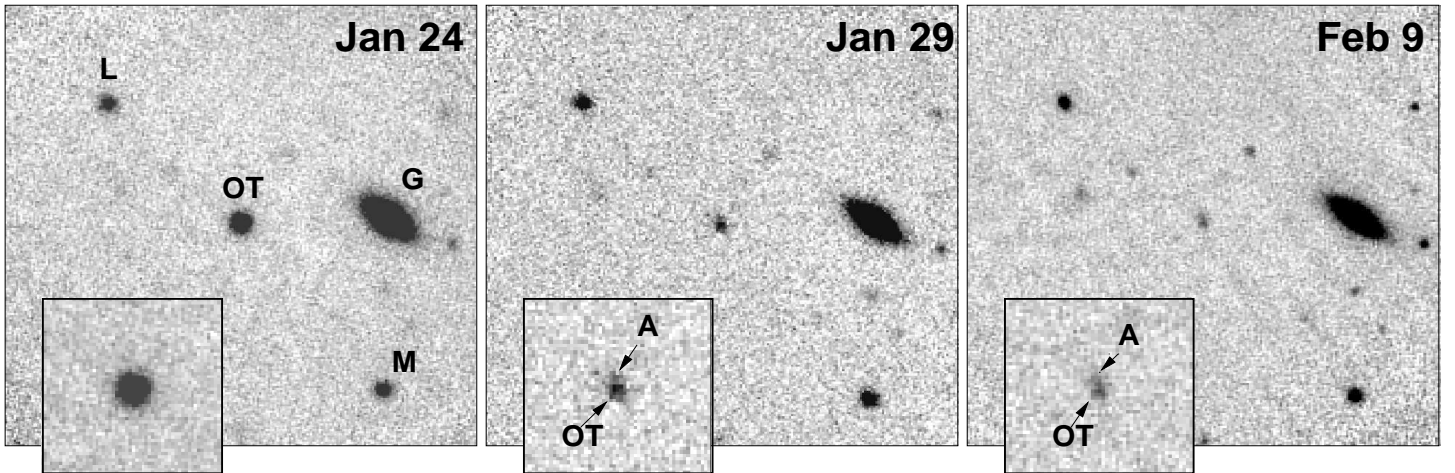
Fig. 1.— Three epochs of Keck I $K$-band imaging of the field of GRB 990123 (24 January 1999 UT, 29 January 1999, and 9 February 1999 UT). The field shown is 32 arcsec × 32 arcsec, corresponding to about 270 physical kpc (710 comoving kpc) in projection at $z = 1.6004$ (for $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 0.2$). The image is rotated to the standard orientation, so that the east is to the left and north is up. In the 24 Jan image, the OT dominates the host galaxy flux, but by 29 Jan the galaxy is resolved (see inset) from the OT.
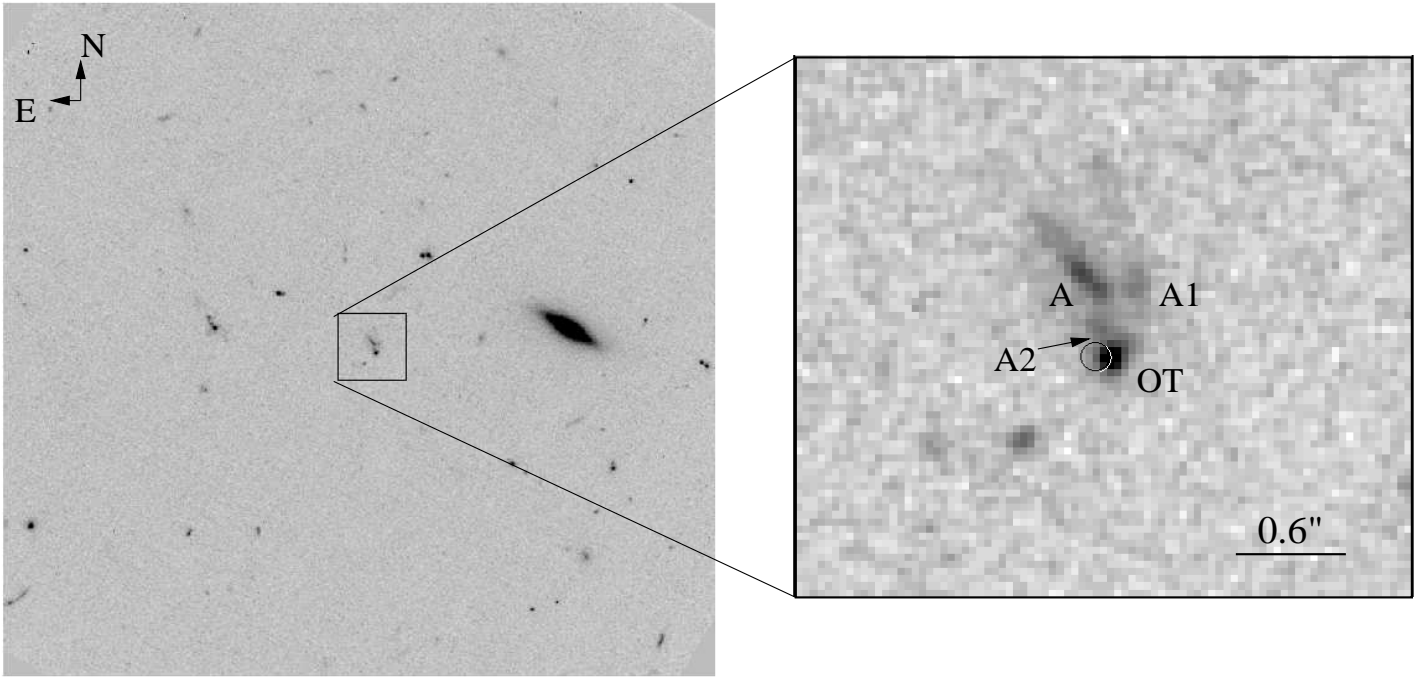
Fig. 2.— (left) The HST STIS image of the field of GRB 990123 rotated to the normal orientation. The field shown is $38 \times 38$ arcsec square, corresponding to about $330 \times 330$ physical kpc square ($850 \times 850$ comoving kpc square) in projection at $z = 1.6004$ (for $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 0.2$). (right) The optical transient (OT), galaxy A (the putative host), and the bright knot (A1) associated with galaxy A are denoted. The ellipse which overlays the OT point-source is the 1-$\sigma$ uncertainty contour for the position of the OT as measured in ground-based imaging (see text). The positional consistency definitely establishes that the point source is indeed the OT. A small nebulousity (A2) just to the north of the OT may be indicative of a star-forming region.
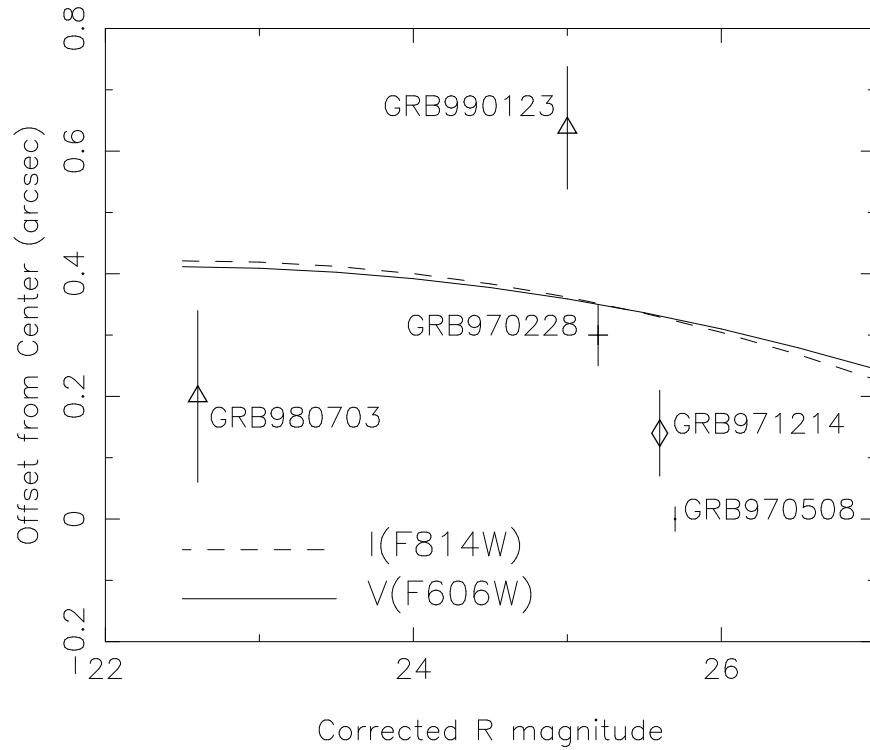
Fig. 3.— Projected separations of OTs from the centers of their host galaxies, as a function of the host galaxy's $R$ band magnitude. Except for GRB 990123, the measured offset of the OT falls within the predicted effective radius (solid and dashed curves) of the host galaxy. Clearly, most GRBs cannot be associated with nuclear activity (e.g. AGN), nor do most GRB events occur far from stellar birth sites within the host galaxy.