The Redshift and the Host Galaxy of GRB 980613: A Gamma-Ray Burst from a Merger-Induced Starburst?  
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Abstract  
We present optical and near-IR identification and spectroscopy of the host galaxy of GRB 980613. The burst was apparently associated with the optically (restframe UV) brightest component of a system of at least five galaxies or galaxy fragments at a redshift of $z = 1.0969$. The component we identify as the host galaxy shows a moderately high unobscured star formation rate, SFR $\sim 5 M_\odot$ yr$^{-1}$, but a high SFR per unit mass, indicative of a starburst. The image components show a broad range of $(R - K)$ colors, with two of them being very red, possibly due to dust. Overall morphology of the system can be naturally interpreted as a strong tidal interaction of two or more galaxies, at a redshift where such events were much more common than now. Given the well established causal link between galaxy mergers and starbursts, we propose that this is a strong case for a GRB originating from a merger-induced starburst system. This supports the proposed link between GRBs and massive star formation.

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

1. Introduction

Studies of the cosmic gamma-ray bursts (GRBs) are currently one of the most active and exciting fields of astrophysics. A deluge of important clues in the long-standing puzzle of GRBs began with the discovery of long-lived X-ray afterglows by the BeppoSAX satellite (Costa et al. 1997). This was followed by the discovery of optical (van Paradijs et al. 1997) and radio afterglows (Frail et al. 1997), and then the first redshift measurement which demonstrated the cosmological nature of GRBs (Metzger et al. 1997). To date, about a dozen redshift measurements of GRBs have been obtained. Studies of afterglows confirmed the synchrotron shock model (e.g., Wijers, Rees & Mészáros 1997), and their physics now seems to be reasonably well understood. For a recent review of observational results, see, e.g., Kulkarni et al. (2000).

What is still not known is what are both the nature of the progenitors and the trigger that causes GRBs. The two currently popular models include mergers of neutron stars or other compact stellar remnants, leading to a creation of a black hole, and a collapsar or hypernova model in which an explosion of a massive star produces a black hole remnant. In both cases, spin energy of a debris torus or of the black hole itself is used to power the GRB. While other models are still viable, there is now a growing evidence in favor of the collapsar/hypernova model, at least for the long-duration bursts detected by BeppoSAX. The most direct evidence favoring this was the probable detection of supernovae associated with GRB 980326 (Bloom et al. 1999) and GRB 970228 (Reichart 1999, Galama et al. 2000), as well as the still controversial case of GRB 980425 and SN 1998bw (Galama et al. 1998, Kulkarni et al. 1998). All models involving massive stars and their remnants suggest that GRBs should be closely related to the massive star formation in galaxies.

Study of GRB host galaxies can provide valuable clues which can constrain the models, and redshifts are necessary in order to derive the physical parameters of the GRBs itself, primarily the energy scale, as well as the hosts: their luminosities, star formation rates, morphology, locations of GRBs within them, etc.

In this Letter we present deep imaging and spectroscopic observations of the host galaxy of GRB 980613. GRB 980613 was detected and localized by BeppoSAX (Piro, Costa et al. 1998; Piro et al. 1998). Following several unsuccessful attempts an optical transient (OT) was discovered by Hjorth et al. (1998). The detection of the host galaxy was reported by Djorgovski et al. (1998a). Its redshift determination was first reported by Djorgovski et al. (1999), and is described in more detail here, with additional data.

2. Observations and Data Reductions

In what follows we assume the Galactic foreground extinction of $A_V = 0.27$ mag (Schlegel, Finkbeiner & Davis 1998), and use the Galactic extinction curve from Cardelli, Clayton, & Mathis (1998) with $R = A_V/E_{B-V} = 3.1$.

Our initial imaging date were obtained on the W. M. Keck Observatory 10-m telescope (Keck II) by Dr. H. Ebeling, on 16.30 June 1998 UT, in the $R$ band, using the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995); two 300 s exposures were obtained. We reduced these images in the standard manner and confirmed that no cosmic rays affected the immediate area of the transient. After the transient had faded we reobserved the field in $R$ band (29 November 1998 UT; 900s), $I$ band (24 March 1999 UT; 1000s), and $K$ band (7 February 1999 UT; 2040s). The final combined images in each filter is shown in fig. 1. The morphology of the system surrounding the GRB is complex. We label 5 distinct components

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1 Partially based on the observations obtained at the W. M. Keck Observatory which is operated by the California Association for Research in Astronomy, a scientific partnership among California Institute of Technology, the University of California and the National Aeronautics and Space Administration.
in fig. 2. Table 1 provides their magnitudes and offsets relative to the position of the OT.

We referenced our $R$ and $I$ band magnitudes using star 2 (Halpern et al. 1998; Diercks et al. 1998). For each component we used a circular aperture and performed an aperture correction using the curve-of-growth of star 2. The total magnitude of system $A+B+C$ is $R = 23.11 \pm 0.05$. We estimate the zeropoint systematic uncertainty due to an uncertain color correction at 0.15 mag. The $2\sigma$ upper limit to a point source detection is $R = 25.9$ mag and $I = 24.9$ mag. Our $K$ band imaging was taken under photometric conditions and we used SJ 9134 (Persson et al. 1998) to obtain a zeropoint for the night. The $K$ band aperture magnitudes of the 5 components are listed in Table 1.

We registered the images from 16 June 1998 and 29 November 1998 $R$ band images using 7 unsaturated stellar objects common to both images within 30 arcsec from the host galaxy. We used the optimum-filter technique in the IRAF package CENTER to position the astrometric tie objects. We determined the rotation, shift, and relative scale of the two images using GEOMAP and then registered the early-time image to the late-time image. The peak of the OT and the putative host were then estimated. Including the peak center errors and the registration uncertainty we find the OT was offset from the brightest $R$ band peak (A) by $0.52'' \pm 0.13''$ East and $0.83'' \pm 0.14''$S. This amounts to a radial angular projected offset of $0.98'' \pm 0.14''$, and we interpret component A as the most likely host galaxy of the GRB. The $I$ and $K$ band images of the host were also registered to the late-time $R$ band image. Fig. 2 shows a color composite 15.3" $\times$ 15.3" region around the GRB and its host using the late-time $R$, $I$, and $K$ band images. The ellipse is a $3\sigma$ error contour about the position of the GRB.

Spectra of the host galaxy were obtained using LRIS on 17 December 1998, 14 January 1999, and 16 February 1999 UT, all in good observing conditions. We used a 1.5 arcsec wide long slit, always at a position angle close to the parallactic. On December 14, we used a 300 lines mm$^{-1}$ grating, giving an effective instrumental resolution FWHM $\approx 16$ A and an approximate wavelength coverage 3950–8950 Å, and obtained 6 exposures totaling 8300 s. On January 14 and February 16, we used a 600 lines mm$^{-1}$ grating, giving an effective instrumental resolution FWHM $\approx 8$ A and an approximate wavelength coverage 5970–8540 and 5700–8270 Å, respectively; 3 exposures of 1800 s were obtained on each night. The object was dithered on the spectrograph slit by several arcsec between the exposures. Exposures of an internal flat-field lamp and arc lamps were obtained at comparable telescope pointings immediately following the target observations. Exposures of standard stars from Oke & Gunn (1983) and Massey et al. (1998) were obtained and used to measure the instrument response curve. We estimate the net flux zero-point uncertainty, including the slit losses, to be about 10–20%.

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**Fig. 1.** Late time images of the field of GRB 980613 with the Keck Telescopes in $R$ (left), $I$ (middle) and $K$ bands (right). Field size is $37'' \times 37''$, with N up and E to the left. The “×” marks the location of the OT. The offset star used for our spectrosopic observations is labeled “S” (the OT was 21.0"N and 3.9"E from the star), as is the Halpern et al. (1998) star “2” used for photometric zeropointing of our $R$ and $I$ band images.

**Fig. 2.** Color composite 15.3" $\times$ 15.3" region around the GRB and its host. We have used the late-time $R$, $I$, and $K$ band images for the red, green, and blue channels. Before combining, we subtracted the mode-determined sky level and scaled each image by the r.m.s. noise of the background. The ellipse is a $3\sigma$ error contour about the position of the GRB. The five distinct components A—E are labeled. The physical scale was computed assuming all objects are in a redshift sheet at $z = 1.096$. As discussed in the text, the GRB appears within the light of component “A”, which we interpret as the host galaxy.
Wavelength solutions were obtained from arc lamps in the standard manner, and then a second-order correction was determined from the wavelengths of isolated strong night sky lines, and applied to the wavelength solutions. This procedure largely eliminates systematic errors due to the instrument flexure, and is necessary in order to combine the data obtained during separate nights. The final wavelength calibrations have the r.m.s. $\sim 0.2 - 0.5$ Å, as determined from the scatter of the night sky line centers. All spectra were then rebinned to a common wavelength scale with a sampling of 2.5 Å using a Gaussian with a $\sigma = 2.5$ Å as the interpolating/weighting function. This is effectively a very conservative smoothing of the spectrum, since it is smaller than the instrumental resolution. Individual spectra were extracted and combined using a statistical weighting based on the signal-to-noise ratio determined from the data themselves (rather than by the exposure time).

The final combined spectrum of the galaxy is shown in fig. 3. A strong [O II] 3727 line emission is present, and a weaker [Ne III] 3869 line is also seen. The observed continuum flux is $F_{\nu} = 0.84$ $\mu$Jy, uncertain by a few percent (statistical). Additional spectrophotometric flux zero-point uncertainty is estimated to be $\sim 10 - 20\%$.

The continuum flux from our direct photometry in the $B$ band, which corresponds roughly to the restframe $B$ band, is $F_{\nu} = 1.15$ $\mu$Jy, uncertain by $\sim 10\%$.

3. DISCUSSION

We will assume a flat cosmology with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Lambda_0 = 0.7$. For $z = 1.0969$, the luminosity distance is $2.461 \times 10^{28}$ cm, and 1 arcsec corresponds to 8.8 proper kpc in projection.

The gamma-ray fluence from this burst was $(1.71 \pm 0.25) \times 10^{-6}$ erg cm$^{-2}$ (Woods et al. 1998). The corresponding isotropic $\gamma$-ray energy is $E_{\gamma,iso} = 6.2 \times 10^{51}$ erg.

From the [O II] 3727 line flux, we derive the line luminosity $L_{3727} = 4.0 \times 10^{41}$ erg s$^{-1}$. Using the star formation rate estimator from Kennicutt (1998), we derive the SFR $\approx 5.6$ $M_\odot$ yr$^{-1}$. From the UV continuum luminosity at $\lambda_{rest} = 2800$ Å, following Madau, Pozzetti & Dickinson (1998), we derive SFR $\approx 3.1$ $M_\odot$ yr$^{-1}$. The difference may be due to the internal reddening within the host galaxy, but we also note that the [O II] line estimator is more sensitive to the current or recent massive star formation than the UV continuum estimator. This is consistent with the presence of the [Ne III] 3869 line, also seen in spectra of some other GRB hosts (Bloom et al. 1998, Bloom, Djorgovski & Kulkarni 2001) which may be indicative of a recent, very massive star formation. We are completely insensitive to any fully obscured star formation component, so that these numbers represent lower limits. The only GRB host galaxy with a higher unobscured SFR measured to date is the host of GRB 980703 (Djorgovski et al. 1998).

From the observed continuum flux in the restframe $B$ band, we derive $M_B = -19.85$ mag, which is about 1 mag fainter than the present-day $L_B$ galaxy. Considering that an average galaxy at this redshift may be $\sim 0.5 - 1$ mag brighter than today due to normal evolution effects, we conclude that this galaxy (A) is moderately underluminous. The star formation rate per unit mass is thus fairly high, consistent with the large equivalent width of the [O II] line. We thus conclude that this galaxy is undergoing a starburst, albeit mild.

However, the most interesting feature may be the morphology of the entire system (A–E), which is highly suggestive of an interaction or early stages of a merger of at least two galaxies, some of which may be partly obscured. Redshifts of all 5 components are necessary to really test this interpretation; we note, however, that we detect a weak [O II] line emission coincident with the component C in our long-slit spectra, at the same redshift as the component A.
Another possibility is that we are seeing a chance superposition of galaxies at very different redshifts, e.g., that the IR-bright components C and D may be unrelated to A (and perhaps also B and E), and if they are in the foreground, some gravitational lensing may be involved. However, we consider this less likely than the interaction/merger hypothesis.

The rate of galaxy interactions and mergers increases sharply with redshift (cf., Le Fèvre et al. 2000), and finding a strongly interacting system at $z \approx 1.1$ is not surprising. The projected separations of components A–E (see fig. 2) are typical of intergalactic separations where dark halos are overlapping and the tidal friction inevitably leads to a merger.

The very red colors of the components C and D, $(R-K) \approx 4.4$ and $> 5.8$, respectively, is naturally explained due to obscuration by dust, which is consistent with the merger hypothesis. Alternatively, they could be passively evolving ellipticals which formed at a very high redshift, which requires some fine-tuning of model parameters.

It is now well established that mergers of gas-rich galaxies lead to bursts of star formation. This may be the strongest case so far for a GRB from such a system. The only other published case to date, showing morphology consistent with a mild tidal interaction is the host galaxy of GRB 990123 (e.g., Bloom et al. 1999, Fruchter et al. 1999, Holland & Hjorth 1999). This provides a further evidence in support of the connection of GRBs with massive star formation.

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REFERENCES


Table 1

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<th>Comp.</th>
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<th>K (mag)</th>
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<td>25.2 ± 0.3</td>
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GRB 980613 host galaxy

$z = 1.0969$