Are Starburst Galaxies the Hosts of Gamma-Ray Bursts？

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ABSTRACT

We present deep 2.2 $\mu$m imaging of twelve gamma-ray burst host galaxies. Template spectral energy distributions are fit to the multiband photometry between visible and near-infrared wavelengths to derive a better constraint on the stellar mass of these galaxies. The internal extinction in the host galaxies is estimated using the rest-frame ultraviolet (UV) slope. We find that the extinction corrected star-formation rates (SFRs) of the galaxies are significantly larger than rates derived from emission lines in the visible or the UV continuum. The ratio between the extinction corrected SFRs and stellar mass for 7 of the host galaxies is high compared to local starbursts and 3 of the hosts have derived far-infrared luminosities comparable to infrared luminous galaxies. In addition, existing observational data reveal that at least 6 of the 11 putative hosts seem to be disturbed or have companion galaxies within a projected angular separation of $\sim$2.5$''$. If we assume that the host and the companion are at similar redshifts, this corresponds to a physical separation of less than 20 kpc, providing some evidence for an ongoing/recent tidal encounter. We conclude that tidally-induced starbursts such as those found in infrared luminous galaxies might be popular birthplaces for gamma-ray bursts. The age of the stellar population in 4 out of 6 galaxies is rather young, of order 10 Myr. This favors models where gamma-ray bursts are due to the core-collapse of isolated, massive stars and explosion of the resultant black hole-accretion disk system.

Subject headings: gamma rays: bursts — cosmology: observations — infrared: galaxies

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1. Introduction

The detection of decaying X-ray, visible, near-infrared and radio transients associated with long duration (> 2 sec) gamma ray bursts (GRBs) has resulted in an accurate localization of the burst positions in the sky (?, e.g.) kul00, piro00, fra97, vanP97. Redshift studies of the transients have confirmed the cosmological origin of at least some of the bursts. After the transients have faded, it has been possible to search for an underlying galaxy which may be associated with the bursts as predicted in most cosmological scenarios for GRBs. The searches have been successful at visible wavelengths with an underlying galaxy (hereafter, a ‘host’) being detected for most of the bursts which have associated transients at other wavelengths (?, e.g.) fra99, blo99a. However, this has provided limited insight into the progenitors of the bursts although observations of the transients have provided many critical constraints for theoretical models of GRBs especially with respect to the energetics and radiation mechanisms in an expanding fireball (?, e.g.) mes97. Since it seems impossible to directly observe the progenitors of the bursts, studying the characteristics of the underlying host galaxy may provide some insight into their origin. For example, if the progenitors of GRBs were massive stars that collapse into black holes (Woosley 1993), GRBs would tend to lie in sites of active star-formation. On the other hand, models that involve coalescing neutron stars or black holes (Narayan et al. 1992) would tend to produce a significant number of bursts that are offset from the nucleus of their hosts because of the large kick imparted to the remnant from its supernova. A third likely possibility is that if GRBs originate in supermassive black holes that constitute the central engine of quasars, one would find the burst positions to be located at the nucleus of galaxies (Roland et al. 1994).

Bloom, Kulkarni & Djorgovski (2001) have compared the observed offset of GRBs from the centers of their host galaxy to the predicted offset for two different GRB models. They find that the median observed offset for the GRBs has a projected distance of 3.1 kpc and that the distribution is inconsistent with a GRB model involving delayed coalescence of stellar remnants which would result in significantly larger offsets between the bursts and the host galaxies (Bloom, Sigurdsson & Pols 1999). However, the observed offsets are consistent with a “collapsar” model involving the explosion of a massive star through a black hole-accretion disk system (MacFadyen & Woosley 1999; Fryer et al. 1999) provided one assumes that massive star formation takes place in an exponential disk. Further tentative evidence for a stellar origin for the bursts comes from the apparent connection between SN1998bw and GRB980425 (Galama et al. 1999) as well as analysis of the light curve at visible bands of GRB980326 and GRB970228 (Bloom et al. 1999b; Galama et al. 2000) both of which showed an increase in brightness ∼3 weeks after the burst. The time evolution of the optical transient brightness for these two cases was interpreted as a power-law GRB light curve coadded on a Type Ic supernova light curve at the appropriate redshift. The two strongest
pieces of evidence though, for an association between GRBs and massive stars comes from the
detection of the host galaxy of GRB980703 at radio wavelengths (Berger, Kulkarni, & Frail
2001) and the X-ray detection of an iron line and the iron-recombination edge in GRB991216
(Piro et al. 2000). The radio detection of the GRB980703 host implies that the galaxy is
undergoing a violent starburst with a star-formation rate in massive stars of $\sim 90$ M$_\odot$/yr.
The detection of the iron line suggests that the GRB progenitor exploded in a mass-rich
environment which probably resulted from recent outflows from the progenitor star. This
appears to disfavor merging black hole-neutron star systems as the cause for GRBs since the
stellar progenitors of these objects would have moved away from their original environments
over the merger timescale.

Recent analysis of the cosmic infrared background and mid- and far-infrared galaxy
number counts have revealed that the bulk of the high-redshift star formation takes place
in dust enshrouded regions (Chary & Elbaz 2001; Xu et al. 2001) and that the UV de-
termined SFRs are a factor of 3−7 lower than the far-infrared determined SFRs. Furthe-
more, at least 70% of this star formation takes place in infrared luminous galaxies with
$L_{\text{IR}} = L(8-1000 \, \mu m) \geq 10^{11} L_\odot$ and which have $\sim 90\%$ of their bolometric luminosity being
emitted at far-infrared (40−500 $\mu$m) wavelengths. These objects are inconspicuous at visible
wavelengths except for the fact that a large fraction of them show irregular morphologies
and strong evidence for interactions. Thus, if GRBs are associated with exploding massive
stars, one would expect their host galaxies to be primarily infrared luminous galaxies.

Interestingly, except for the hosts of GRB980703 and GRB980613 (Berger, Kulkarni, &
Frail 2001; Djorgovski et al. 2001), none of the other host galaxies studied so far show
evidence of starbursts or abnormally high star formation rates based on measurements of
the UV continuum or O II line strength (e.g. Bloom et al. 1999a, Odewahn et al. 1998).
Furthermore, none of the hosts have been detected by SCUBA (Smith et al. 1999), the
submillimeter instrument on the JCMT which has been extremely successful in detecting
high-redshift ultraluminous infrared galaxies (ULIGs). However, the SCUBA observations
were typically sensitive to an 850 $\mu$m flux density of $3\sigma \sim 6$ mJy restricting their ability to
only detect galaxies at the tip of the far-infrared luminosity function which account for less
than 10% of the dust enshrouded star-formation.

Near-infrared ($1.0 < \lambda < 2.5 \, \mu m$) observations are well suited for establishing the
characteristics of the hosts. At $z < 2$, K-band (\(\lambda = 2.2 \, \mu m\)) observations trace the rest-frame
stellar mass of galaxies which would provide a better estimate of galaxy morphology. At
higher redshifts, the peak of the blue light from recent star-formation would be redshifted

\footnote{ULIGs have $L_{\text{IR}} > 10^{12} L_\odot$ while luminous infrared galaxies (LIGs) have $10^{12} > L_{\text{IR}} > 10^{11} L_\odot$.}
into the K-band providing a better estimate of the unobscured star-formation rate. This, in conjunction with the visible light observations, which trace the rest-frame UV light provides an estimate of the rest-frame UV–visible slope and thereby the amount of dust obscuration in the galaxy. Lastly, for low galactic latitude fields, near-infrared observations are less affected by Galactic extinction which is patchy and whose distribution is not well understood.

Thus to provide a better study of GRB host galaxy properties, we obtained deep K-band images of some GRB fields whose positions were accurately determined by the detection of transients at other wavelengths. These are GRB970228, GRB970508, GRB971214, GRB980326, GRB980329, GRB980519, GRB980613, GRB980703, GRB981220, GRB990123, GRB991208 and GRB000301C. The transient had faded to below detection limits by the time of the observations so the photometry is uncontaminated by the light from the afterglow. Most of these sources have also been shown to have an underlying host galaxy at visible wavelengths. We use our observations in conjunction with the existing photometry and redshift data in the literature to constrain star formation rates and derive information about the characteristics of GRB hosts.

2. Observations and Reduction

The near-infrared observations were made using the NIRC instrument (Matthews & Soifer 1994) at the f/25 focus of the 10m Keck I telescope on UT Nov 29-Dec 1 1998, Jan 11-12 1999, Jan 29-Jan 30 1999, Apr 28-29 1999 and Apr 19 2000. NIRC contains a 256×256 InSb array with a pixel size of 0.15″ implying a field of view of 38.4″ × 38.4″. A standard K filter (λ₀ = 2.21μm, Δλ=0.4μm) and K_s filter (λ=2.16μm, Δλ=0.3μm) was used. The nights of Nov-Dec 1998 and Apr 28, 1999 were not photometric. Observations were made by dithering in a random pattern with integrations of duration 8×15s (coadds×exposure) or 12×5s per position. Table 1 summarizes the observations, along with typical seeing values and sensitivities. Seeing values were determined from the full width at half maximum (FWHM) of field star profiles. Several standards from the *Hubble Space Telescope* faint standard lists were observed over each night (Persson et al. 1998).

Clipped averages of the dark current images were subtracted from all the frames taken over a night. Bad pixels were masked as were bright field sources. These dark-subtracted masked frames were then median-ed together and normalized to create a sky superflat. In the reduction of the individual object frames, appropriate sky frames were generated from the masked images to minimize any pattern that may persist in the reduced frames because of the presence of bright sources in the field. The generated sky was normalized to the object frame by the ratio of the modes and subtracted. A second order sky was also fit to
the individual frames and subtracted. The dark and sky subtracted, flatfielded images were stacked and averaged by aligning on one of the bright, unsaturated, field stars. The typical point source sensitivity in our final, reduced images was $1\sigma \sim 24$ mag in the K-band.

In almost all the cases, deep visible light observations have indicated the presence of an underlying host galaxy (Table 2). Photometry on our infrared images was performed in a beam centered on the position of the host galaxy. If the host was undetected in the visible light images, the beam was centered at the position of the radio or visible light transient which was determined by aligning an earlier epoch observation which detected the transient and other reference objects in the field with our final reduced frames. Corrections for the finite beam size was applied by curve of growth analysis of one of the field star profiles. Atmospheric extinction corrections ($\sim 0.05$ mags/airmass) were also applied. The few observations that were done in non-photometric conditions had other photometric data available (except GRB980329) which served as a basis for performing relative photometry with respect to field objects. For GRB980329, the photometry was performed using the average zero point from two observations of a standard which were taken just prior and 2 hours prior to the target frames. Any variation of the zero point during the observations of the burst field was monitored by photometry on a field star. The zero point varied by less than 0.1 mag over the period of the observations and hence we conclude that our derived upper limit is reliable.

Table 2 shows the observed parameters of GRB host galaxies$^6$. Wherever possible, observations that are further in time from the burst i.e. “late-time”, are listed to minimize the effect of afterglow contamination. In cases where late-time visible photometry is not available, the published magnitudes for the host have been derived from a fit to the integrated light of the transient and the host, assuming a power-law decay of the transient and a constant brightness for the underlying host. For the analysis, the magnitudes were corrected for Galactic extinction based on the model of Schlegel et al. (1998). The Galactic extinction values are shown in Table 3 and an $R_V = A_V / E(B-V)$ of 3.1 was adopted. Extinction at other wavelengths was calculated using the Galactic extinction curve of Mathis (1990). The derived luminosity of the galaxies between UV and near-infrared wavelengths that is shown in Table 3, is derived by integrating over the spectral energy distribution derived from the multiband photometry. For the luminosity distances, an $\Omega_{m,0} = 0.3$, $\Lambda_0 = 0.7$, $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ cosmology was adopted.

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$^6$It should be noted that some of the magnitudes are based on observations with the HST/STIS clear filter and the transformation to standard V-magnitudes is a function of the color of the objects and therefore quite uncertain.
3. Characteristics of GRB Hosts

3.1. Morphology and Companions

The effect of redshift induced band-shifting on morphology of galaxies has been well demonstrated in the Hubble Deep Field-North (Bunker et al. 2000; Dickinson 2000; Corbin et al. 2001). High redshift galaxies appear to be more irregular at observed blue wavelengths than at red/near-infrared wavelengths. This is because $z > 1$ galaxies have their rest-frame UV light, which is dominated by patchy star-formation, redshifted into the visible bandpasses. In addition, extinction in the UV is much stronger than in the visible, amplifying the irregular distribution of UV light. In contrast, the rest-frame visible and near-infrared light from these galaxies which is dominated by main sequence stars and K giants respectively, is less extincted and is redshifted into the K-band. Of the GRB hosts listed in Table 2, GRB970228, GRB971214, GRB980519, GRB980613 and GRB990123 show somewhat distorted morphologies at visible wavelengths (see references in Table 2). In comparison, GRB970228, GRB980519, GRB980613, GRB981220, GRB990123 are significantly extended in the K-band images. In addition, 8 of the 12 bursts (GRB970228, GRB971214, GRB980519, GRB980613, GRB980703, GRB981220, GRB990123, GRB991208, GRB000301C) show the presence of one or more companion galaxies within $\sim 2.5''$ of the burst position (Figure 1). At a depth of $K=23$ mag, the number density of galaxies is about $10^5$ deg$^{-2}$ or $7.7 \times 10^{-3}$ arcsec$^{-2}$ (Djorgovski et al. 1995). Hence, the probability that 7 of the reliably determined hosts (except GRB981220) would have companion galaxies within a 2.5'' radius represents an overdensity by an order of magnitude and seems intriguing. In comparison, only about 20% of the field galaxies observed at visible wavelengths seem to show evidence of a companion within the same projected distance at redshifts $\sim 1$ (Le Fevre et al. 2000). Although the sample size is small, at least for some of the listed cases, it seems reasonable to surmise that the companion galaxy is tidally interacting with the host, inducing a starburst that could provide the progenitors of gamma-ray bursts.

3.2. Extinction-corrected Star Formation Rates

We now attempt to derive physical properties of the host galaxies such as the amount of internal extinction and the extinction-corrected SFR from their rest-frame UV photometry using the $\beta-$slope technique described in Meurer et al. (1999).

The $\beta-$slope technique was developed because a large fraction of the visible/UV light in starbursts/infrared luminous galaxies is thermally reprocessed by dust into the far-infrared. The relative attenuation of the visible/UV light is dependent on the relative extinction
properties of dust at those wavelengths. So, a measurement of the UV slope traces the
amount of dust extinction in the galaxy and except for the most luminous far-infrared sources,
provides a good measure of the star-formation obscured by dust. The technique fails for
ULIGs in that it provides only a strong lower limit to the opacity and thereby the amount of
dust-obscured star-formation. This is because ULIGs have regions of very high dust opacity
\( \tau_{UV} \gg 1 \) where all the UV photons are thermally reprocessed by the dust grains. As
a result, the UV-slope of a ULIG is sensitive only to the light coming from optically thin
regions \( \tau_{UV} \lesssim 1 \) and does not trace the rate of star-formation in the high opacity regions.

Using the photometry in Table 2, we determined the rest-frame UV slope \( (\beta) \) shortward
of about 350 nm which for most galaxies, since they are at \( z > 1 \), is derived from a power
law fit to the B, V and R-band observed magnitudes. It should be emphasized that this is
an extremely liberal definition of the UV-slope primarily because the broadband photometry
could be contaminated by absorption and emission lines. Secondly, the uncertainty in the
photometry is substantial and the measurements are consistent with a wide range of UV
slopes which translate to large uncertainties in the derived extinction values. For example, a
20% error in the UV-slope measurement results in a 0.4 mag error in the derived extinction
at UV wavelengths and a 50% uncertainty in the dust-obscured SFR value. This effect is
particularly important for GRB970228, GRB971214 and GRB991208, all of which have only
observations at two filters tracing the UV light. Lastly, for the low redshift objects, the
V-band traces rest-frame 320 nm which is much longer than the 250 nm adopted by Meurer
et al. (1999) for performing the calibration between the UV-slope and the FIR luminosity.
This does not seem to be a significant problem if the starburst extinction law of Calzetti et
al. (2000) is adopted. This is because, for a young stellar population, even large values of
extinction such as \( A_V \sim 2 \) mag, result in an observed spectrum which can be well fit by a
single power law between 100 nm and 400 nm.

After estimating the UV-slope, we use the relationship derived by Meurer et al. (1999):

\[
A_{1600} = 4.43 + 1.99\beta
\]

\[
\log[L_{\text{FIR}}/\nu L_\nu(1600)] = \log(10^{0.4A_{1600}} - 1) + 0.076
\]

to determine the far-infrared luminosity of the galaxy. In the above equations, \( A_{1600} \) is the
extinction at 160 nm which in the Calzetti et al. (2000) extinction law is \( \sim 2.4 \) \( A_V \) and
in the Galactic extinction law is \( \sim 2.6 \) \( A_V \), where \( A_V \) is the extinction in the V-band. The
far-infrared luminosity is typically about 83% of the total infrared luminosity which can then
be transformed into a SFR. The calibration of Kennicutt (1998) yields:

\[
\rho \left( M_\odot \text{ yr}^{-1} \right) = 1.71 \times 10^{-10} \left( L_{\text{IR}}/L_\odot \right)
\]

From this, we can derive a lower limit to the true SFR which is typically higher than the
UV-derived value. The value is a lower limit because, for reasons mentioned earlier, Meurer et al. (2000) find that the \( \beta \)-slope technique underestimates the far-infrared luminosity of ULIGs which contribute \( \sim \)30\% of the global star-formation at high redshift. Thus, we derive dust-enshrouded SFRs of 1.6, 2.5, 70, 30, 7, 8 \( M_\odot \)/yr for the host galaxies of GRB970228, GRB970508, GRB980613, GRB980703, GRB990123, GRB991208. The corresponding \( A_{1600} \) values are 2.3, 2.5, 4.5, 2.2, 1.2, and 3.8 mag while the predicted lower limits to their infrared luminosity \( L_{\text{IR}} \) are \( 9.3 \times 10^9, 1.4 \times 10^{10}, 4 \times 10^{11}, 1.7 \times 10^{11}, 3.8 \times 10^{10} \) and \( 4.5 \times 10^{10} \) \( L_\odot \) respectively. The object with the one of the highest SFR here, GRB980703, was also detected in the radio by Berger, Kulkarni, & Frail (2001) but the SFR in massive stars derived from the radio luminosity is about a factor of 3 higher.

There is some uncertainty in the V-band photometry of GRB971214 which differs by about a magnitude between Odewahn et al. (1998) and Sokolov et al. (2001). If we adopt a geometric mean of the two values which corresponds to \( V = 26.2 \pm 0.3 \) mag, then the rest-frame UV slope suggests an average \( A_V \sim 1.8 \) mag. An empirically derived correction of \( \beta_{\text{phot}} - \beta_{\text{spec}} = 0.5 \) has been applied in the derivation of the UV-slope of GRB971214 to account for the difference between a spectroscopically derived UV-slope and the slope derived from broadband photometry (Meurer et al. 1999). This difference is due to stellar and interstellar absorption features which redden the flux at these UV wavelengths. The derived infrared luminosity corresponding to this UV-slope is \( 2 \times 10^{12} \) \( L_\odot \) and the SFR is \( 340 \) \( M_\odot \)/yr which would make it a starburst comparable to the host of GRB980703. Further high quality multiband photometry at visible wavelengths is required to assess the accuracy of this unusually high number since our value is a lower limit as explained earlier, and is barely consistent with the submillimeter upper limit of Smith et al. (1999). The possibility of AGN contamination also cannot be ruled out although the spectra presented in Kulkarni et al. (1998) do not show any broad lines.

Thus, we find that the internal extinction in GRB hosts calculated from their UV slope is significant, with an average value of \( A_V \sim 1.2 \) mag which is similar to that derived by Sokolov et al. (2001). As a result, the dust-enshrouded SFR values derived above are typically higher than those derived from observations of the UV continuum (Table 3). However, the total (obscured+UV) star-formation rate in these galaxies is still not unusually high. It is useful to note that although only 2 of the galaxies have derived \( L_{\text{IR}} > 10^{11} \) \( L_\odot \) and high resultant SFRs, the ratio between the dust-obscured SFR and the unobscured SFR (i.e. the ratio between column 7 and column 6 in Table 3, excluding GRB971214) for the GRB hosts has an average value of \( \sim 4 \). This is in agreement with the redshift dependent value of 3–7 that Chary & Elbaz (2001) find for the ratio between the global comoving dust-obscured star-formation rate and the unobscured star-formation rate derived from the UV continuum.
3.3. Mass and Age Estimates

In this section, we calculate the SFR per unit stellar mass ($\dot{M}/M$) of the GRB host galaxies. Our K-band data allows a better constraint on the stellar mass of the host galaxy than derived by Sokolov et al. (2001) which was based in most cases on B, V, R, I photometry. For this purpose, we used the newest version (year 2000) of the population synthesis spectral energy distributions (SEDs) of Bruzual & Charlot (1993) considering templates with both solar and 0.02 times solar metallicity. A variety of star-formation histories of the form $\exp(-t/\tau)$ are selected for the templates, ranging from $\tau$ of 1 Myr which corresponds to a single, brief epoch of star-formation, to near-constant with a $\tau$ of 10 Gyr. Screen extinction internal to the host galaxy was also incorporated using the extinction curve of Mathis (1990) and the starburst extinction curve of Calzetti et al. (2000). The fits were performed by minimizing the sum of absolute errors weighted by the photometric uncertainty at each of the wavelengths. The parameters that are derived from the fits to the observed magnitudes are the total stellar mass ($M_{\text{gal}}$), internal extinction ($A_V$), age of the starburst ($t$), template metallicity and $e$-folding timescale of the starburst ($\tau$). Of these, the metallicity and $e$-folding timescale are relatively unconstrained by the quality of the available photometry. The range of acceptable values for the three other parameters i.e. mass, age and extinction, are obtained from fits with different constraints e.g. with and without extinction, Galactic extinction and starburst extinction, low metallicity and high metallicity. The true statistical uncertainty in the parameters derived from these fits is much larger as has been illustrated in Papovich, Dickinson, & Ferguson (2001).

GRB970228: The host of GRB970228 has been found to have a redshift of 0.695 (Bloom et al. 2001). It has a roughly circular/irregular morphology in HST images but displays no evidence of an ongoing tidal interaction. The intrinsic color of the host is quite blue, rather typical of field galaxies and suggestive of active star formation (Fruchter et al. 1999). However, analysis of the visible light spectrum by Bloom, Kulkarni & Djorgovski (2001) seems to suggest uniform star-formation if internal extinction is negligible, rather than a few hundred Myr old starburst derived in the analysis of Castander & Lamb (1999). The derived luminosity at visible wavelengths is $\sim$0.1 $L_\odot$ i.e. quite sub-luminous. Estimates of the SFR from the O II line flux and UV luminosity provide a value $\sim$0.5 $M_\odot$/yr (Bloom et al. 2001). As a result, it has been classified as a late-type dwarf by Bloom et al. (2001) and the observed magnitudes fit by a reddened Sc galaxy template by Galama et al. (2000). Estimates of the mass of the galaxy have thus far been poorly constrained. If we assume no extinction or the starburst extinction curve, our template fits yield a mass for the host galaxy of $1.2-2\times10^8 M_\odot$, $t \sim 40-80$ Myr and $\tau = 1-20$ Myr with $A_V < 0.2$ mag. If we instead adopt the Galactic extinction curve, the derived range of values depending on the metallicity are $A_V \sim 0.2-0.9$ mag, $M_{\text{gal}} \sim 1.6-2.5\times10^8 M_\odot$, $t = 20-140$ Myr and $\tau = 20-70$ Myr. This
latter estimate of $A_V$ agrees with that derived from the $\beta$-slope technique. However, for this galaxy, both the B-band and V-band photometry used to derive the UV-slope have large uncertainties associated with them. So the amount of dust extinction in this galaxy derived from the $\beta$-slope technique is somewhat uncertain. Irrespective of this, the $M/M_*$ ratio for the host is rather high while the age of the stellar population in the best-fitting templates are low, suggestive of a recent starburst in this dwarf galaxy (Figure 2). For reference, the brightness of the galaxy 2.5" to the NE of the host is $K = 21.6 \pm 0.1$ mag.

GRB970508: Bloom et al. (1998) confirmed that the redshift of the GRB970508 host galaxy is 0.835. HST/STIS observations (Fruchter et al. 2000) revealed that the galaxy is quite compact and that the GRB was centered within $\sim 70$ pc of the nucleus of the galaxy. The host has an intrinsic luminosity at visible wavelengths of $\sim 0.1 L_\odot$, again suggesting a dwarf galaxy with a UV-derived SFR of $0.2-1.4 M_\odot/yr$. In the absence of extinction, we find the mass of the galaxy to be $3.4 \times 10^8 M_\odot$ with $t \sim 100$ Myr and $\tau = 1-10$ Myr. If we consider the Galactic extinction curve, we find that the observed flux densities are best fit by a low metallicity template with $A_V \sim 0.8$ mag, $M_{\text{gal}} \sim 8 \times 10^7 M_\odot$, $t = 7$ Myr and $\tau = 1$ Myr. This value is in good agreement with the estimate of internal extinction derived from the $\beta$-slope technique.

There are three other possibly unrelated galaxies in the vicinity of the host which are denoted by G1, G2 and G3 in Zharikov et al. (1998). For reference, we derive the brightness of G1, G2 and G3 to be $K = 22.1 \pm 0.1$ mag, $20.5 \pm 0.1$ mag and $21.6 \pm 0.1$ mag respectively. There is a fourth object $\sim 6''$ N-NW of the host with $K = 21.3 \pm 0.1$ mag which we call G4. To the best of our knowledge, the redshifts of these individual objects have not been measured.

GRB971214: HST imaging revealed a galaxy of irregular morphology with rest frame luminosity $L_{\text{UV}} \sim 0.2 L_\star$ (Odewahn et al. 1998). It has a measured redshift of 3.418 (Kulkarni et al. 1998). The results from our template fitting method are quite uncertain since there are measurements at only 3 bands of which the photometry in the V-band differs by more than 1 magnitude between Sokolov et al. (2001) and Odewahn et al. (1998). We adopt a weighted geometric mean of the two V-band measurements which results in $V = 26.2 \pm 0.3$ mag. In addition, interstellar absorption features, Ly$\alpha$ emission and the Lyman forest could be responsible for contaminating the V and R-band photometry for which we have applied an empirical correction in the derivation of the UV-slope but not to the individual photometry values. Since the age of the Universe at $z = 3.418$ is 1.7 Gyr, this places an additional constraint on the template ages in our fits to the multiband photometry. Fits without extinction result in $M_{\text{gal}} \sim 8 \times 10^9 M_\odot$ with $t \sim 200$ Myr and $\tau \sim 30$ Myr. Fits including extinction ($A_V \sim 0.5$ mag) suggest higher masses and older stellar populations with $M_{\text{gal}} \sim 1-5 \times 10^{10} M_\odot$, $t \sim 100-700$ Myr, $\tau \sim 0.03-2$ Gyr. The UV slope suggests an
average $A_V \sim 1.8$ mag for the UV light, an infrared luminosity of $2 \times 10^{12} \, L_\odot$ and a SFR of $\sim 350 \, M_\odot/yr$. This is quite similar to the $3\sigma$ upper limit of 3 mJy obtained for this galaxy at 850 $\mu$m which at $z = 3.418$, translates to $L_{IR}$ for the galaxy of $3.3 \times 10^{12} \, L_\odot$ (Smith et al. 1999). However, the best-fitting exponentially decaying star-formation history results in a galaxy mass that exceeds the derived stellar mass. While it is possible that this is a massive galaxy undergoing a violent starburst, we conclude that better multiband photometry at visible wavelengths is required to determine the true parameters of this galaxy. For reference, the brightness of the galaxy located 2″ to the W-NW is $K = 21.5 \pm 0.1$ mag.

GRB980326: The HST/STIS observations of Fruchter et al. (2001a) yielded a tentative detection of the host galaxy with $V = 29.3 \pm 0.3$ mag but the object is too faint for any other characteristics to be derived. When the HST image is aligned with ours, the flux in our image at the position of the galaxy corresponds to $K = 22.9 \pm 0.4$ mag. The presence of bright stars in the frame and high residuals in that part of the image reduces the credibility of this detection. For reference, the object 2.4″ to the East has $K = 21.1 \pm 0.1$ mag.

GRB980329: Holland et al. (2000) provided tentative evidence for a host galaxy located about 0.5″ southwest of the position of the optical transient with $R \approx 28$ mag. Again, the object is too faint at visible wavelengths and undetected in the near-infrared for any characteristics of the host to be derived. However, it does seem that the Djorgovski et al. (1998b) measurement of the GRB980329 host is contaminated by the optical transient.

GRB980519: Visible light observations of GRB980519 revealed a faint underlying galaxy as well as a companion galaxy 1.5″ to the SW (Holland et al. 2000). The host has $V = 28 \pm 0.3$ mag while the companion has $V = 27 \pm 0.1$ mag. Our infrared observations confirm the detection of the combined system with $K = 22.5 \pm 0.3$ mag. However, the object is at the limit of detectability and as a result we are unable to derive any physical parameters for the host.

GRB980613: The GRB apparently originated in an interacting system at $z = 1.097$, where the host has at least 2 faint galaxy companions and 2 bright ones all of which are seen in the visible image and denoted A (host), B, C, D, E (Djorgovski et al. 2001). We found values of $K = 21.7 \pm 0.2$ mag, $21.6 \pm 0.2$ mag, $20.2 \pm 0.2$ mag, $20.3 \pm 0.2$ mag and $22.3 \pm 0.2$ mag for A, B, C, D and E respectively, in reasonable agreement with the K-band values of Djorgovski et al. (2001). Components A and E are relatively blue compared to components B, C and D. The SFR as derived from the visible/UV emission is $\sim 5 \, M_\odot/yr$ and its luminosity is lower than present-day $L_*$ galaxies leading Djorgovski et al. (2001) to conclude that the galaxy is undergoing a mild starburst. Fits to the multiband photometry without extinction are quite poor. Fits including extinction ($A_V = 1 - 2$ mag) yield a mass of $M_{gal} = 0.5 - 2.6 \times 10^9 \, M_\odot$, $t = 3 - 8$ Myr and $\tau = 1 - 30$ Myr. The lower limit to the obscured
SFR derived from the $\beta$-slope technique is $70 \, M_\odot/yr$ with $A_V = 1.8 \, \text{mag}$. Alternatively, applying an extinction-correction to the SFR derived from the UV continuum results in $60 \, M_\odot/yr$, in excellent agreement with our $\beta$-slope value.

GRB980703: This is one of the brightest hosts seen in our sample and is located at $z = 0.966$ (Djorgovski et al. 1998a). HST/STIS imaging has determined that it is a very compact galaxy with a faint companion galaxy $\sim 2''$ to the S-SE (Holland et al. 2001). If the internal extinction is assumed to be negligible, the SFR derived from the UV continuum and the OII line flux is in the range 8-20 $M_\odot/yr$ (Djorgovski et al. 1998a). While there is evidence for extinction in this galaxy based on the X-ray/visible/near-infrared light curve of the transient (Castro-Tirado et al. 1999), the range of values span a wide range, from $A_V = 0.3$ mag to 2.2 mag. The galaxy has also been detected at radio wavelengths by Berger, Kulkarni, & Frail (2001). The radio luminosity of the galaxy yields a SFR from massive stars ($M > 5 \, M_\odot$) of $\approx 90 \, M_\odot/yr$. This has been extrapolated using a Salpeter mass function to yield a total SFR of $500 \, M_\odot/yr$. The derived far-infrared luminosity, adopting the relation derived by Condon (1992), is greater than $10^{12} \, L_\odot$, clear evidence that this galaxy is a ULIG. Furthermore, the position of the GRB is very close to the nucleus of the galaxy, suggestive of an origin in a nuclear starburst.

Template fits to the multiband photometry with no extinction are rather poor. If we include extinction, $A_V$ spans the range 0.3–1.2 mag, $t=10–30 \, \text{Myr}$, $M_{\text{gal}}=1–4.6 \times 10^9 \, M_\odot$ and $\tau=1–20 \, \text{Myr}$. The $\beta$-slope technique yields a lower limit of $A_V \sim 0.9 \, \text{mag}$ and an obscured SFR of $30 \, M_\odot/yr$. Assuming an $A_V \sim 1 \, \text{mag}$ results in an extinction corrected SFR from the UV continuum of $45 \, M_\odot/yr$. The SFR estimate from the extinction-corrected UV continuum is in excellent agreement with that obtained from the sum of the $\beta$-slope technique and the observed UV continuum. Furthermore, this value is within a factor of 2 of the SFR in massive stars derived from the radio luminosity. This curious agreement between the SFR in massive stars and our extinction-corrected values provides weak evidence for the star-formation in this galaxy to be biased towards the high mass end. Alternatively, it is possible that much of the star-formation in this galaxy is in optically thick regions and as a result, insensitive to measurements in the UV.

GRB981220: A radio transient presumably associated with GRB981220 was detected within a few days of the burst (Galama et al. 1998). Bloom et al. (1999c) found a variable source in their visible light images located at the position of the radio transient and which was therefore presumed to be the visible light afterglow superposed on the host. Later VLBA observations of the radio transient revealed that it has a core-jet morphology extending to the S-W (Taylor et al. 1999). This was therefore interpreted to be an intraday variable source unrelated to the GRB. However, the brightness of this source has not varied over
the two epochs of the infrared observations and it is extended in the NE-SW direction in seeing conditions of 0.5″. There is also an excess of flux 1.3″ to the west which we refer to as a “companion”. The brightness of the object and companion are K=19.0±0.1 mag and 22.0±0.3 mag respectively. Comparison with published visible light photometry (Bloom et al. 1999c) indicates the object is very red (R−K=7.4±0.5 mag) compared to the other host galaxies which would indicate it to be either a unique host or a source that has varied between the time of the visible light and infrared observations. The companion (object 'K' in Bloom et al.) is relatively bluer at (R−K=3.5±0.5 mag) and similar in color to the other hosts. While it is possible that this is an interacting system, the association of these objects to GRB981220 is unclear but probably spurious since the discussed source is outside the refined IPN error box of the burst.

GRB990123: HST/STIS imaging of the host galaxy of GRB990123 indicates that it has a disturbed morphology (Bloom et al. 1999a; Fruchter et al. 1999b) with knots of star-formation which have been denoted as A, A1, A2, #1 and B. Analysis of the STIS data by Holland & Hjorth (1999) provided magnitudes of V=28.1±0.3 mag for knots A1, A2 and #1. The host which is presumed to be knot A since it is the brightest object in the system, is located at a redshift of 1.6 (Andersen et al. 1999; Kulkarni et al. 1999) and has a V magnitude of 24.25±0.2 mag (Fruchter et al. 1999b; Holland & Hjorth 1999). The derived SFR for knot A is ∼4 M⊙/yr and its blue luminosity L_B∼0.5L*.

It has also been shown that the galaxy is quite blue but not very luminous for galaxies at that redshift. Interestingly, our estimate of the internal extinction in this host is quite small. We find A_V=0.5 mag based on the β-slope technique while the template fits to the multiband photometry yield A_V=0 mag, M_gal=3.6 × 10^9 M⊙ with t = 140−180 Myr and τ ∼ 30 Myr. This could be interpreted as evidence that not all interacting systems necessarily result in strong star-formation in dust-enshrouded regions. On the other hand, it is equally likely that there are regions of strongly obscured star-formation that are located in the midst of the detected knots of emission but they are optically thick to UV light. Good observational evidence for such a hypothesis comes from the “Antennae” galaxy which shows strong mid-infrared emission arising from warm dust in regions that are inconspicuous in UV light (Mirabel et al. 1998). So it is possible that the integrated SFR for the system is actually much higher than the sum of it’s parts. It should also be noted that for this galaxy, much of the early photometry for the host galaxy was performed by masking or fitting the
point source corresponding to the transient. This seems to induce a significant inaccuracy in the early-time photometry values as is illustrated in the difference between the values of Sokolov et al. (2001) and Fruchter et al. (1999b) and between our near-infrared values and those derived by Bloom et al. (1999a).

GRB991208: The near-infrared image of GRB991208 reveals the host and a companion galaxy ‘A’ about 1″ SE of the host which is also seen in the HST/STIS image (Castro-Tirado et al. 2001). There appears to be an additional object ‘B’ that is 2.5″ East and slightly North of the host which is not visible in the STIS image but it is not clear from the image if these objects are connected by a tidal stream. The brightness of the host galaxy, galaxy ‘A’ and ‘B’ are K=21.7±0.2 mag, 23.1±0.4 mag and 22.4±0.2 mag respectively. The V−K color of the host, which is compact in the HST images, is 3.0±0.3 mag (Castro-Tirado et al. 2001). If all these galaxies are at a z ~ 0.7 as inferred for the GRB (Dodonov et al. 1999; Djorgovski et al. 1999), their projected physical separation is about 7 kpc/arcsec. It is necessary to measure the redshift of these three objects to establish any dynamical interaction between them. Castro-Tirado et al. (2001) inferred from the broadband photometry that the galaxy is not exceptionally bright and has a SFR of ~5−18 M⊙/yr. The best fits to the multiband photometry result from low metallicity templates with little or no extinction. The derived mass of the host is $8.6 \times 10^8$ M⊙ for $\tau \approx 70$ Myr and $t \sim 300$ Myr. The low value of extinction is inconsistent with our estimate from the β-slope technique. However, we conclude that the UV-slope result for this galaxy is uncertain for reasons mentioned in Section 3.2.

GRB000301C: The HST/STIS image of Fruchter & Vreeswijk (2001) with the transient was aligned with our image and photometry performed at the position of the transient. This yielded a magnitude of K=23.0±0.5 mag. We do not have full confidence in this detection since the observed brightness of the host is significant only at the ~2.5σ level. However, if the measurement is real, it must be the host galaxy because the transient should have faded to a level fainter than ~24 mag (Rhoads & Fruchter 2001). When compared with the V-band photometry of Fruchter & Vreeswijk (2001), the host galaxy has an observed V−K color of 5.0±0.6 mag which is redder than most hosts. The companion galaxy located at an angular separation of 2.3″ to the north-west (18 kpc projected distance) has a brightness of K=19.8 ± 0.1 mag which results in R-K= 4.5 ± 0.3 mag. However, there is no evidence of any tidal debris between the burst position and this galaxy. For reference, the bright star located to the south-west has a brightness of K=16.02±0.05 mag.

Although the masses derived for individual GRB host galaxies from the different fits span a relatively narrow range, the statistical uncertainty in the derived masses can be quite large, about an order of magnitude depending on the photometric uncertainties. In addition, fitting a single template to the multiband photometry often results in the lowest mass system
because of the low mass-to-light ratio of a young stellar population. Papovich, Dickinson, & Ferguson (2001) have demonstrated that including an older stellar component in the fits typically results in an upper limit on the mass which is a factor of 2−3 higher than that derived from fitting a single template. Irrespective of this, the sense of Figure 2 remains the same even if the masses of the GRB hosts were corrected upwards by a factor of 3.

In addition, fits which include stellar populations of two different ages result in a lower age for the component of stars formed in the more recent starburst. The presence of young stellar populations (<10⁸ yr) in GRB host galaxies, combined with their high star-formation rate per unit stellar mass seems to suggest that most GRB host galaxies have undergone a recent starburst. The age of the stellar populations is comparable to the lifetimes of massive (>10 M☉) stars providing some evidence for GRBs originating from collapsars rather than from the inspiral and merger of double degenerate objects which can typically take a few hundred Myr from the onset of star-formation (Fryer et al. 1999).

4. Conclusions

Of the 12 putative gamma-ray burst positions that were observed, all except GRB981220 had definite identification of a visible light transient associated with the burst. For the remaining 11 bursts, visible light observations of the transient position detected an underlying host galaxy after the transient had faded. Our observations reveal that at least 6 of the 11 hosts appear to be in systems with another galaxy within a projected angular separation of 2.5 ″. We have derived extinction corrected star-formation rates for 7 of the hosts which have measured redshifts using the UV-slope technique. In addition, we have derived other physical parameters of the host galaxies such as their mass, age of the starburst, and internal extinction based on fits to the multiband photometry between visible and near-infrared wavelengths. We find that the extinction corrected star-formation rates are significantly higher than the estimates derived from rest-frame UV continuum emission and the O II line strengths. More interestingly, the star formation rates per unit stellar mass (Ṁ/M) of these galaxies is higher than for typical nearby starburst galaxies. In addition, the template fits to 4 of the objects provide evidence of a young stellar population of age about 10−50 Myr, a typical timescale for the formation of a ‘collapsar’ through the core collapse of an isolated massive star and explosion of the resultant black hole/accretion disk system. The high incidence of GRB hosts in close pairs of galaxies and high Ṁ/M values strengthen the argument that the progenitors of at least some of the long duration GRBs are high-mass stars in starbursts. High quality multiband photometry of a statistically large sample of host galaxies will be required to assess if the stellar mass function in high redshift starbursts is
biased towards the high mass end.

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Fig. 1.— Deep K-band images of selected GRB host galaxies where North is up and East to the left. The images are 15" on a side and the host is either located at the center of the field or marked with a circle. In many cases a companion galaxy can be seen within about 2.5" radius of the host. From left to right, top to bottom, the images are of 970228, 970508, 971214, 980326, 980519, 980613, 980703, 981220, 990123, 991208.
Fig. 2.— Total (obscured+unobscured) star formation rates for the gamma-ray burst host galaxies derived using the $\beta$—slope technique plotted against the ratio between the star formation rates and the midpoint of the range of stellar masses derived from fits to the multiband photometry (Table 3 has the stellar mass from the best-fitting templates). The uncertainty on the GRB971214 point is quite large because of the lack of good photometry at multiple wavelengths. The star-formation rates for the GRB hosts are lower limits (see text), so the data points are likely to move higher and to the right. Estimates of the stellar mass typically have 95% confidence intervals that span an order of magnitude. Also plotted are the corresponding values for two prototypical starbursts Arp220 and M82 and the relatively quiescent Sbc galaxy M51 (Silva et al. 1998). GRB hosts have star-formation rates per unit stellar mass much higher than local starbursts.
Table 1. Summary of observations

<table>
<thead>
<tr>
<th>Source</th>
<th>RA (J2000)</th>
<th>Dec</th>
<th>UT Date(^d)</th>
<th>On source time seconds</th>
<th>Seeing FWHM</th>
<th>Sensitivity (^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB970228</td>
<td>05:01:46.7</td>
<td>11:46:53</td>
<td>Jan 11.4, 12.3</td>
<td>12840</td>
<td>0.51(^\prime\prime)</td>
<td>23.7</td>
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<td>GRB970508</td>
<td>06:53:49.5</td>
<td>79:16:20</td>
<td>Nov 30.5</td>
<td>7080(^a,b)</td>
<td>0.47(^\prime\prime)</td>
<td>22.6</td>
</tr>
<tr>
<td>GRB971214</td>
<td>11:56:26.4</td>
<td>65:12:01</td>
<td>Jan 12.5</td>
<td>7200</td>
<td>0.6(^\prime\prime)</td>
<td>23.2</td>
</tr>
<tr>
<td>GRB980326</td>
<td>08:36:34.3</td>
<td>-18:51:24</td>
<td>Jan 11.5, 12.4</td>
<td>11625</td>
<td>0.63(^\prime\prime)</td>
<td>23.0</td>
</tr>
<tr>
<td>GRB980329</td>
<td>07:02:38.0</td>
<td>38:50:44</td>
<td>Dec 2.4</td>
<td>5220(^a,b)</td>
<td>0.4(^\prime\prime)</td>
<td>22.8</td>
</tr>
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<td>GRB980519</td>
<td>23:22:21.5</td>
<td>77:15:43</td>
<td>Jan 11.2, 12.2</td>
<td>10200</td>
<td>0.9(^\prime\prime)</td>
<td>23.0</td>
</tr>
<tr>
<td>GRB980613</td>
<td>10:17:57.6</td>
<td>71:27:26</td>
<td>Jan 11.6</td>
<td>7275</td>
<td>1.0(^\prime\prime)</td>
<td>23.1</td>
</tr>
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<td>GRB980703</td>
<td>23:59:06.7</td>
<td>08:35:07</td>
<td>Jan 11.2</td>
<td>1350</td>
<td>0.55(^\prime\prime)</td>
<td>22.4</td>
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<tr>
<td>GRB981220</td>
<td>03:42:28.9</td>
<td>17:09:15</td>
<td>Jan 11.3</td>
<td>2700</td>
<td>0.5(^\prime\prime)</td>
<td>22.8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Jan 30.3</td>
<td>2400</td>
<td>0.84(^\prime\prime)</td>
<td>22.5</td>
</tr>
<tr>
<td>GRB990123</td>
<td>15:25:30.3</td>
<td>44:45:59</td>
<td>Jan 29.7</td>
<td>1800</td>
<td>0.8(^\prime\prime)</td>
<td>23.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Apr 28.6</td>
<td>2340</td>
<td>0.75(^\prime\prime)</td>
<td>22.3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Apr 29.6</td>
<td>5700(^b)</td>
<td>0.5(^\prime\prime)</td>
<td>23.0</td>
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<tr>
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<td>46:27:21</td>
<td>Apr 19.5</td>
<td>2880</td>
<td>0.8(^\prime\prime)</td>
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<td>29:26:36</td>
<td>Apr 19.6</td>
<td>3600</td>
<td>0.7(^\prime\prime)</td>
<td>22.6</td>
</tr>
</tbody>
</table>

\(^a\)Observations made in K\(_s\) filter

\(^b\)Non-photometric conditions

\(^c\)In a beam of diameter 1.5\(^\prime\prime\). The sensitivity was calculated from the standard deviation in the background values.

\(^d\)Dates are Nov 29-Dec 1 1998, Jan 11-12 1999, Jan 29-30 1999, Apr 28-29 1999 and Apr 19 2000