THE ASTROPHYSICAL JOURNAL, 560:652–658, 2001 October 20

THE HOST GALAXY OF GRB 980703 AT RADIO WAVELENGTHS—A NUCLEAR STARBURST IN AN ULTRALUMINOUS INFRARED GALAXY

E. BERGER AND S. R. KULKARNI
Division of Physics, Mathematics, and Astronomy, California Institute of Technology, 105-24, Pasadena, CA 91125; ejb@astro.caltech.edu, srk@astro.caltech.edu

AND

D. A. FRAIL
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; dfrail@nrao.edu
Received 2001 May 4; accepted 2001 June 15

ABSTRACT

We present radio observations of GRB 980703 at 1.43, 4.86, and 8.46 GHz for the period of 350–1000 days after the burst. These radio data clearly indicate that there is a persistent source at the position of GRB 980703 with a flux density of approximately 70 μJy at 1.43 GHz and a spectral index $\beta \approx 0.32$, where $F_\nu \propto \nu^{-\beta}$. We show that emission from the afterglow of GRB 980703 is expected to be 1–2 orders of magnitude fainter and therefore cannot account for these observations. We interpret this persistent emission as coming from the host galaxy—the first example of a γ-ray burst (GRB) host detection at radio wavelengths. We find that it can be explained as a result of a star formation rate (SFR) of massive stars ($M > 5\ M_\odot$) of $\approx 140\ M_\odot\ \mathrm{yr}^{-1}$, which gives a total SFR ($0.1\ M_\odot < M < 100\ M_\odot$) of $\approx 750\ M_\odot\ \mathrm{yr}^{-1}$. On the basis of these data alone we cannot rule out that some fraction of the radio emission originates from an obscured active galactic nucleus. Using the correlation between the radio and far-IR (FIR) luminosities of star-forming galaxies, we find that the host of GRB 980703 is at the faint end of the class of ultraluminous infrared galaxies, with $L_{\mathrm{FIR}} \sim 10^{12}\ L_\odot$. From the radio measurements of the offset between the burst and the host and of the size of the host, we conclude that GRB 980703 occurred near the center of the galaxy in a region of star formation. A comparison of the properties of this galaxy with radio and optical surveys at a similar redshift ($z \approx 1$) reveals that the host of GRB 980703 is an average radio-selected star-forming galaxy. This result has significant implications for the potential use of a GRB-selected galaxy sample for the study of galaxies and the intergalactic medium at high redshifts, especially using radio observations, which are insensitive to extinction by dust and provide an unbiased estimate of the SFR through the well-known radio-FIR correlation.

Subject headings: cosmology: observations — galaxies: high-redshift — galaxies: starburst — gamma rays: bursts — radio continuum: general — stars: formation

1. INTRODUCTION

Recent studies of the properties and host galaxies of γ-ray bursts (GRBs) reveal some indirect evidence for the link between GRBs and star formation. Optical measurements of the offset distribution of GRBs from their host centers appears to be consistent with the distribution of collapsars in an exponential disk but inconsistent with the expected offset distribution of delayed binary mergers (Bloom, Kulkarni, & Djorgovski 2001). GRB 990705 is an illustrative example of this result since *Hubble Space Telescope* (*HST*) images revealed that the burst was situated in a spiral arm, just north of an apparent star-forming region (Holland et al. 2001; Bloom et al. 2001). The absence of optical afterglows from the so-called dark GRBs (Djorgovski et al. 2001) points to the association of GRBs with heavily obscured and possibly star-forming regions. In addition, Galama & Wijers (2001) claim high column densities toward several GRBs from X-ray observations of afterglows

Consequently, one of the pressing questions in the study of GRB host galaxies is whether they are representative of star-forming galaxies at a similar redshift. If they are, then the dust-penetrating power of GRBs and their broadband afterglow emission offer a number of unique diagnostics of their host galaxies: the obscured star formation fraction, the interstellar medium within the disk, the local environment of the burst itself, and the global and line-of-sight extinctions, to name a few.

GRB 980703, which has one of the brightest (apparent magnitude) hosts to date ($R \approx 22.6$ mag; Bloom et al. 1998; Vreeswijk et al. 1999), offers an excellent opportunity for detailed studies. The afterglow optical and near-IR (NIR) light curves exhibited pronounced flattening about 6 days after the burst, and this was attributed to an underlying bright host (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999). Djorgovski et al. (1998) undertook spectroscopic observations of the host and obtained a redshift of 0.966. Using three different estimators ([O II], Hα, and 2800 Å UV continuum) of the star formation rate (SFR), Djorgovski et al. (1998) inferred extinction-corrected SFRs of 10–30 $M_\odot\ \mathrm{yr}^{-1}$.

Here we report radio observations of GRB 980703 covering the period 350–1000 days after the burst at three frequencies: 1.43, 4.86, and 8.46 GHz. This burst has the distinction of being followed up for 1000 days; the previous record holder was GRB 970508 (445 days; Frail, Waxman, & Kulkarni 2000). The organization of the paper is as follows: We summarize the radio observations and data reduction in § 2. In § 3 we summarize the main observational results. In § 4 we show that the late-time radio observations require a steady component over and above the decaying afterglow observations. We argue that this component is unlikely to arise from an unobscured active galactic nucleus (AGN) but is instead due to star formation. In § 5, we infer the SFR from the radio observations and

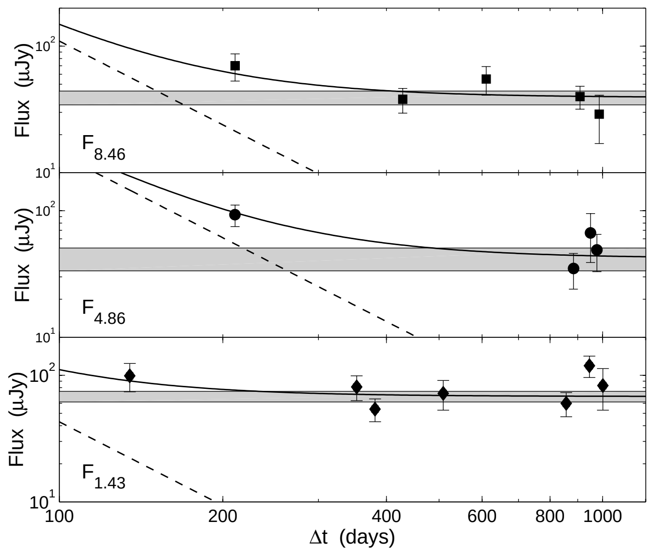

FIG. 1.—Radio light curves at 1.43, 4.86, and 8.46 GHz. The thin solid lines are the combined afterglow and host galaxy emission, the dashed lines indicate the afterglow emission, and the thick solid lines are the weighted-average fluxes of the host galaxy, with the thickness indicating the uncertainty in the flux. Only measurements at $t \gtrsim 350$ days after the burst were used to calculate the host flux. The fits are based on broadband fitting (E. Berger et al. 2001, in preparation). The data clearly indicate that there is a constant component in the observed emission, interpreted as the host galaxy. For details of the data reduction and analysis, see § 2.

compare and contrast this estimate to those derived from optical observations. Thanks to the high angular resolution and accurate astrometry of radio observations, we are able to derive an accurate offset between the burst and the centroid of the host, as well as constrain the size of the radio-emitting region (§ 6).

2. RADIO OBSERVATIONS

Very Large Array (VLA)[1] observations of GRB 980703 were initiated on 1998 July 4.40 (UT) at 4.86 GHz. All observations were obtained in the standard continuum mode with two 50 MHz contiguous bands. We used the extragalactic sources J2330+110, J0010+109, and J0022+061 for phase calibration and 3C 48 (J0137+331) and 3C 147 (J0542+498) for flux calibration. We used the Astronomical Image Processing System (AIPS) for data reduction.

Late-time observations (time after the burst, $t \gtrsim 350$ days) were co-added over a period of a few to 30 days in order to increase the overall sensitivity of each detection. This is appropriate since the expected change in the flux density from the afterglow over a few days, several hundred days after the burst, is negligible relative to the associated errors in the measurements. A log of the late-time observations and the flux density measurements are summarized in Table 1, and the light curves are shown in Figure 1. A summary of the early radio data as well as broadband modeling is given in E. Berger et al. (2001, in preparation).

[1] The VLA is operated by the National Radio Astronomy Observatory (NRAO), a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

3. RESULTS

From Figure 1, we see that the late-time ($t \gtrsim 350$ days) radio light curves do not exhibit the customary power-law decay expected of afterglows but instead show flattening. Using all the measurements in Table 1, we find the following weighted-average flux densities for the host galaxy of GRB 980703: $F_{\nu,8.46} = 39.3 \pm 4.9$ μJy, $F_{\nu,4.86} = 42.1 \pm 8.6$ μJy, and $F_{\nu,1.43} = 68.0 \pm 6.6$ μJy. We searched for but did not find evidence for significant variability over the 650 day monitoring period (see Fig. 2). From these flux densities we find that the radio spectral index is $\beta = 0.32 \pm 0.12$, where $F_\nu \propto \nu^{-\beta}$.

The radio images also allow us to determine the projected angular offset between the host galaxy and afterglow of GRB 980703. For each individual detection, positions were determined from Gaussian fits, and the host-GRB offset was calculated with respect to a Very Long Baseline Array (VLBA) position that was measured to 0."0007 accuracy in each coordinate on 1998 August 2 at 8.42 GHz (E. Berger et al. 2001, in preparation). These offsets are displayed in Figure 3, and the combined value from all observing runs is

TABLE 1

RADIO OBSERVATIONS OF GRB 980703

Epoch (UT) (1)	Δt (days) (2)	Array Configuration (3)	$t^{\text{on-source}}$ (hr) (4)	ν_0 (GHz) (5)	$S \pm \sigma$ (μJy) (6)	δR.A. (arcsec) (7)	δDecl. (arcsec) (8)
1999 Jun 15.36–26.29	352.65	A	6.5	1.43	81 ± 18	-0.17 ± 0.17	0.03 ± 0.17
1999 Jul 10.53–28.28	381.22	A	13.4	1.43	54 ± 10	0.07 ± 0.09	-0.04 ± 0.09
1999 Aug 19.40–Sep 21.24	428.64	A	11.3	8.46	38 ± 8	-0.06 ± 0.02	0.03 ± 0.02
1999 Nov 24.06	508.88	B	1.7	1.43	72 ± 11	0.01 ± 0.03	-0.03 ± 0.03
2000 Mar 5.70	610.52	BnC	2.8	8.46	55 ± 19	-0.16 ± 0.18	-0.26 ± 0.18
2000 Oct 7.30–Nov 19.08	847.01	A	6.5	1.43	60 ± 13	0.01 ± 0.13	-0.03 ± 0.13
2000 Dec 2.19–4.97	882.60	A	4.9	4.86	35 ± 11	-0.12 ± 0.08	0.02 ± 0.08
2000 Dec 21.15–2001 Jan 4.98	908.38	A	7.0	8.46	40 ± 8	0.02 ± 0.03	0.03 ± 0.03
2001 Feb 2.00–4.93	945.29	AnB	1.9	1.43	119 ± 23	-0.65 ± 0.30	-0.23 ± 0.30
2001 Feb 8.08	949.90	AnB	1.2	4.86	67 ± 28	1.22 ± 0.67	-0.38 ± 0.67
2001 Mar 2.98–9.00	975.81	B	4.5	4.86	49 ± 16	-1.21 ± 0.49	0.02 ± 0.49
2001 Mar 13.97–17.98	985.80	B	4.5	8.46	29 ± 12	0.45 ± 0.43	0.02 ± 0.43
2001 Mar 22.96–Apr 8.56	1001.08	B	2.6	1.43	83 ± 30	-1.26 ± 1.76	-1.23 ± 1.76

NOTE.—Col. (1): UT date of the start of each observation or range of dates for observations that were added over several days. Col. (2): Time elapsed since the γ-ray burst. Col. (3): Array configuration. Col. (4): Total on-source observing time. Col. (5): Observing frequency. Col. (6): Peak flux density at the best-fit position of the radio transient, with the error given as the rms noise on the image. Col. (7): Projected angular offset in R.A. between the host center and the position of GRB 980703. Col. (8): Projected angular offset in declination.

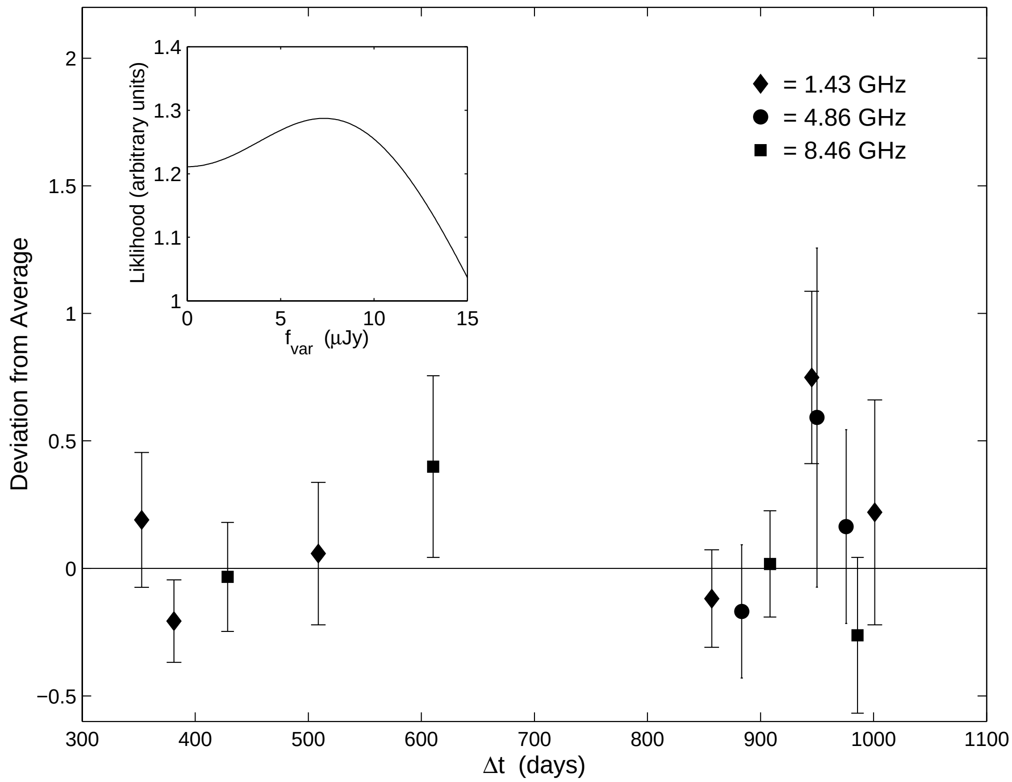

FIG. 2.—Fluctuations of individual measurements around the weighted average presented by the wide strips in Fig. 1. We note that there are no fluctuations above 1.1 σ at 8.46 GHz, 0.8 σ at 4.86 GHz, and 1.7 σ at 1.43 GHz, indicating that the flux in each band is consistent with a constant. In fact, if we assume that the source has some variability (over that due to measurement errors), then the variable flux is less than ± 7 μJy, with a 40% probability that there are no fluctuations at all (see insert). This conclusion supports the hypothesis that the radio emission is not due to an unobscured AGN.

shown in the insert. We find an average offset from all measurements of $-0''.032 \pm 0''.015$ in R.A. and $0''.024 \pm 0''.015$ in declination. The uncertainty in the position of the source is given by $\delta\theta_{\rm offset} \approx (\theta_{\rm synbeam}/2)/({\rm S/N})$, where $\theta_{\rm synbeam} \approx \lambda/B_{\rm max}$ is the half-power synthesized beamwidth (HPBW), λ is the observing wavelength, $B_{\rm max}$ is the length of the maximum baseline, and S/N is the signal-to-noise ratio of the flux measurement.

The optical measurements of Bloom et al. (2001) for the host of GRB 980703 give an angular offset of $-0''.054 \pm 0''.055$ in R.A. and $0''.098 \pm 0''.065$ in declination (see insert in Fig. 3). They conclude that GRB 980703 was not significantly offset from the center of its host galaxy, in agreement with the more accurate offset measurements in the radio.

In addition to accurate measurements of the offset, the radio observations allow us to place meaningful limits on the size of the radio-emitting region (i.e., the size of the star-forming region). We find that in our highest resolution images the source is unresolved, and therefore, based on the synthesized beam size, we can derive an upper limit on the physical size of the source. For our adopted cosmological parameters (§ 5), we find that the angular diameter distance to the source is $d_A \approx 6.7 \times 10^{27}$ cm. The full synthesized beamwidth at 8.46 GHz is $\theta_{\rm HPBW} \approx 0''.27$, which gives an upper limit of $D_{\rm rad} = d_A\,\theta_{\rm HPBW} < 2.8$ kpc on the diameter of the source.

4. EVIDENCE FOR HOST GALAXY EMISSION IN THE RADIO REGIME

An afterglow origin is difficult to reconcile with the properties of the late-time radio emission. From the early broadband data, it was inferred that the afterglow spectrum peaked at frequency $\nu_m \sim 4 \times 10^{12}$ Hz at $t = 1.2$ days (Vreeswijk et al. 1999). If the explosion was spherical, then we expect $\nu_m \propto t^{-3/2}$ (Sari, Piran, & Narayan 1998; Chevalier & Li 2000). Thus, the radio emission at 8.46 GHz is expected to decay for $t > 70$ days after the burst, while the emission at 1.43 GHz will decay for $t > 240$ days after the burst. If the ejecta were collimated (opening angle, θ_j), then we expect a more rapid decay, $\nu_m \propto t^{-2}$, once the bulk Lorentz factor, Γ, of the flow falls below θ_j, $\Gamma(t) \lesssim \theta_j^{-1}$ (Sari, Piran, & Halpern 1999). In this case, we expect the radio afterglow to start decaying at even earlier times, and the flux will decay faster relative to a spherical explosion. In either case, we expect the radio afterglow to decay by at least a factor of 3 over the time span under consideration, 350 days $< t <$ 1000 days.

We can clearly see from Figure 1 that this decay is not taking place and the flux instead remains constant over a period of approximately 650 days. This behavior is similar to the flattening observed in the optical/NIR light curves of several GRBs (including GRB 980703), when the emission from the afterglow decays below the level of emission from the host galaxy.

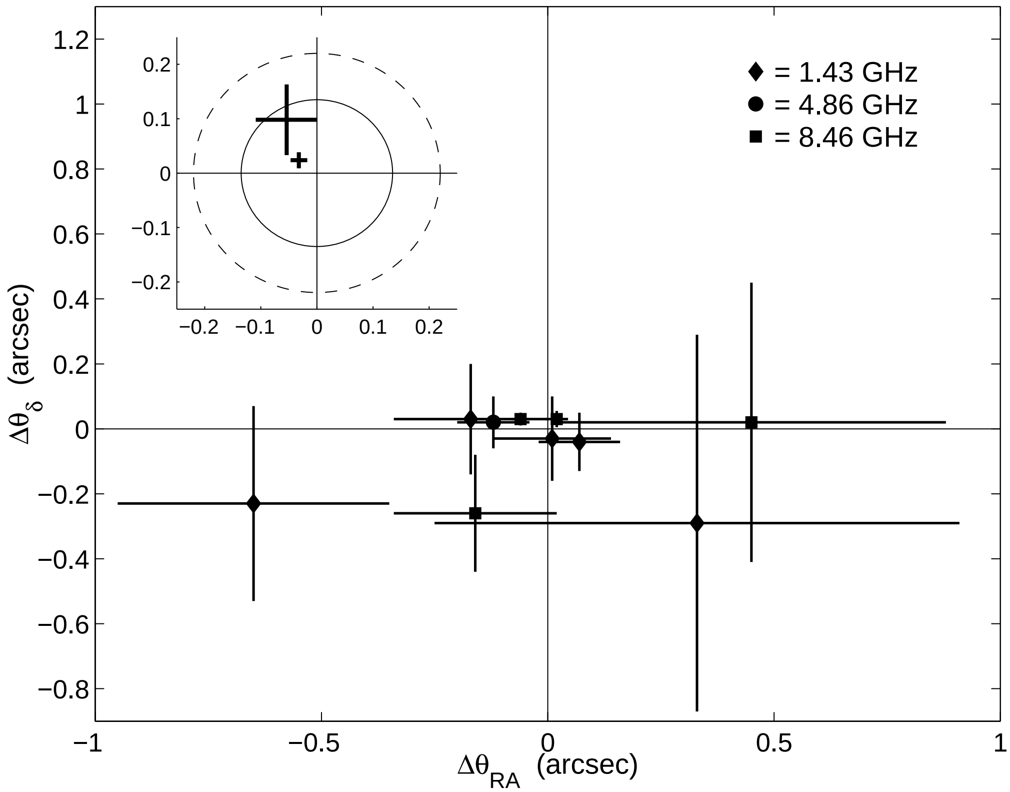

FIG. 3.—Offset measurements for all epochs in which the host galaxy emission dominates and for which the measurements are accurate to more than 0".5. The plot shows the offset in R.A. and δ of the VLBA position of the burst (see § 6) relative to the host center, $(\Delta\theta_{\rm R.A.}, \Delta\theta_{\delta}) = (0, 0)$. The most accurate measurements are at 8.46 GHz in the VLA A configuration. In this mode we achieved an rms positional error of 0".02. The insert shows the weighted-average offset in both R.A. and δ (*small cross*). The larger cross is the offset measurement from Bloom et al. (2001). The solid circle designates the projected maximum source size from the radio observations in the A configuration at 8.46 GHz, and the dashed circle is the optical size from Holland et al. (2001). Clearly, the formation of massive stars is concentrated in the central region of the host. The small offset of the burst from the host center indicates that GRB 980703 occurred within the region of star formation, which points to a link between GRBs and massive stars.

Furthermore, the afterglow spectrum is expected to be a power law, $F_\nu \propto \nu^{-\beta}$, where $\beta = (p-1)/2$ and p is the power-law index of the Lorentz factor distribution of the shocked electrons, $N(\gamma)\,d\gamma \propto \gamma^{-p}\,d\gamma$ for $\gamma > \gamma_{\rm min}$ (Sari et al. 1998). From the observations of many afterglows, we note that p is in the range 2.2–2.6, and thus we expect $\beta \sim 0.7$; for GRB 980703 the spectral index inferred from the optical data by several groups ranges from 0.6 to 1 (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999). However, the observed spectral index in the range 1.43–8.46 GHz is much lower, $\beta = 0.32 \pm 0.12$. We thus conclude that there exists a steady source of emission other than the afterglow.

It is instructive to compare the characteristics of the radio emission toward GRB 980703 with those of other galaxies at a similar redshift. A radio survey of the Hubble Deep Field (HDF) and its flanking fields showed that the mean spectral index of the 8.46 GHz–selected sample is $\langle\beta_{8.46}\rangle = 0.35 \pm 0.07$ (Richards 2000). In a survey of two $7' \times 7'$ fields with the VLA at 8.44 GHz, Windhorst et al. (1993) found for sources with a flux density $\lesssim 100$ μJy (hereafter "μJy sources") a median spectral index, $\beta_{\rm med} \approx 0.35 \pm 0.15$, and Fomalont et al. (1991) found $\beta_{\rm med} \approx 0.38$ for μJy sources selected at 4.9 GHz. Thus, the host galaxy of GRB 980703 appears to be a normal μJy source compared to sources selected at 4.9 or 8.5 GHz. In addition, it has been noted (Richards 2000) that the spectral index of radio sources selected at frequencies larger than 5 GHz flattens from a value of approximately 0.7 for the mJy ($F_\nu \gtrsim 1$ mJy) population to 0.3 for μJy sources.

The reason for the flattening of the spectral index may be the varying ratio of thermal bremsstrahlung to synchrotron emission for galaxies undergoing a burst of star formation. Supernova remnant shock acceleration of electrons results in synchrotron emission, with a characteristic spectral index of ≈ 0.8 (Condon 1992). On the other hand, thermal bremsstrahlung emission from H II regions, excited by star formation, has a much flatter spectral index, $\beta \approx 0.1$. Thus, as the direct contribution from massive stars increases, the spectra are expected to flatten from a value of 0.8 to 0.1. This is exactly the effect that is observed in the aforementioned surveys.

Within the HDF and the Small Selected Area 13 (SSA13), Richards et al. (1999) identified radio sources with fluxes in the range 10–100 μJy with bright disk galaxies with $I \approx 22$ mag. The $I-K$ color for these galaxies is approximately 2.5 mag. Bloom et al. (1998) find $I \approx 21.9$ mag and $I-K \approx 2.1$ mag for the host of GRB 980703. Thus, we see from both the radio spectrum of the source and the optical I mag and $I-K$ color that the host galaxy of GRB 980703 has the characteristics of a typical star-forming radio galaxy selected at 8.5 GHz.

An alternate explanation for the radio emission is that it originates from an AGN. It has been noted in surveys of the HDF, its flanking fields, and SSA13 that approximately 20% of the radio sources are AGNs with spectral indices of about 0.3 (Richards et al. 1999; Richards 2000; Barger, Cowie, & Richards 2000). Windhorst et al. (1993) found a similar result in their survey of two $7' \times 7'$ fields at 8.44 GHz. Thus, there is a modest probability that the emission from the host of GRB 980703 is due to an AGN.

We consider the AGN hypothesis unlikely based on the radio data and optical spectroscopy. Optical spectra of the source obtained by Djorgovski et al. (1998) show no evidence for an unobscured AGN: high-ionization lines such as Mg II λ2799, [Ne V] λ3346, and [Ne V] λ3426 are absent, and the [O III] λ4959–to–Hβ ratio is approximately 0.4, much lower than [O III]/Hβ > 1.3 for AGNs (Rola, Terlevich, & Terlevich 1997). Another way to discriminate between AGNs and star-forming galaxies is to correlate the [O II] equivalent width (EW) with continuum color (Dressler & Gunn 1982). Kennicutt (1992) showed that AGNs have redder colors for similar [O II] EWs, relative to normal galaxies. Using the spectrum presented in Djorgovski et al. (1998), we evaluate the color index (41–50) $\equiv$ 2.5 log $[f_\nu(5000\ \mathring{A})/f_\nu(4100\ \mathring{A})]$ (Kennicutt 1992) and find it to be 0 ± 0.1; an AGN with the same [O II] EW would have a value $\gtrsim 0.3$ (Kennicutt 1992). Finally, Rola et al. (1997) found that for a sample of emission-line galaxies at $z \sim 0.8$, the color index between the continuum underlying the Hβ and [O II] λ3727 lines is ≥ 0.4 for all AGNs in their sample. Using the spectrum of Djorgovski et al. (1998), we find that this color index is approximately zero.

A second but less persuasive argument against an AGN origin is the apparent absence of significant radio variability over the 650 day monitoring period (see Fig. 2). The radio cores of most, but not all, low-luminosity AGNs show variability exceeding the observed levels (Falcke et al. 2001).

In summary, we conclude that the radio emission seen from the host of GRB 980703 is dominated by star formation. We note, however, that the arguments presented above are not sufficient to rule out the presence of an *obscured* AGN. Determining the degree to which active star formation and/or a central engine contribute to the total emission is a common problem with centimeter- and submillimeter-selected galaxies (e.g., Ivison et al. 2000). X-ray observations by *Chandra* or *XMM* may be needed to conclusively show which is the dominant power source. In the next section we assume that the bulk of the radio emission is due to star formation and show that the host is a typical radio galaxy at $z \sim 1$ undergoing star formation.

5. THE STAR FORMATION RATE IN THE HOST GALAXY OF GRB 980703

Star formation is traced by optical, far-IR, submillimeter, and radio emission. In the following we will use the radio data to estimate the SFR in the host galaxy of GRB 980703 and then compare the results with the SFR derived from optical indicators and with radio surveys at a similar redshift range in order to place the host of GRB 980703 in a larger context.

5.1. *Star Formation Rate from the Radio Observations*

Condon (1992) showed that the total radio luminosity is a combination of synchrotron and thermal emission components, both directly related to the formation rate of massive stars via a simple relationship. Moreover, since the lifetime of massive stars is of the order of 10^7 yr and the lifetime of the synchrotron-emitting electrons is of the order of 10^8 yr (Condon 1992), the radio emission is an excellent probe of the instantaneous SFR.

From the redshift of GRB 980703, $z = 0.966$ (Djorgovski et al. 1998), and the cosmological parameters $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$, and $H_0 = 65$ km s^{-1} Mpc^{-1}, we find that the luminosity distance to the burst is $d_L = d_A(1+z)^2 \approx 2.6 \times 10^{28}$ cm, and the observed luminosity at each frequency is given by $L_\nu = 4\pi d_L^2 F_\nu$. The emitted luminosity is given by $L_{\mathrm{em},\nu'} = L_{\mathrm{obs},\nu}(\nu/\nu')^\beta(1+z)^\beta$, where β is the spectral index of the radio emission, ν' is the source-frame frequency, and ν is the observing frequency. The radio spectral index derived in § 3 is $\beta = 0.32 \pm 0.12$, and thus the emitted luminosity in each frequency is approximately 25% higher than the observed luminosity at the same frequency.

The emitted luminosity at $\nu' = 1.43$ GHz is $L_{\mathrm{em}}(1.43) = (7.2 \pm 0.9) \times 10^{30}$ ergs s^{-1}, and we find that the SFR of massive stars in the host of GRB 980703 is

$$\mathrm{SFR}(M > 5\ M_\odot) \approx \frac{L_{\mathrm{em}}(1.43)}{5.3 \times 10^{28} \nu_{\mathrm{GHz}}'^{-\beta} + 5.5 \times 10^{27} \nu_{\mathrm{GHz}}'^{-0.1}} \approx 140\ M_\odot\ \mathrm{yr}^{-1}\ . \quad (1)$$

Since both the thermal and nonthermal components are proportional only to the formation rate of high-mass stars, equation (1) has to be modified by a factor that accounts for the contribution from stars in the mass range 0.1–5 $M_\odot$. For a Salpeter initial mass function (IMF), this factor evaluates to 5.5. We use the Salpeter IMF since it is already implicitly used in equation (1) for the mass range 5–100 $M_\odot$. Thus, within this framework the total SFR is ≈ 750 $M_\odot$ yr^{-1}.

Haarsma et al. (2000) derived the SFR for radio galaxies in the HDF, its flanking fields, SSA13, and V15 in the redshift range 0.85–1.15. These fields have been observed to μJy sensitivities at centimeter wavelengths, and the detected radio sources have been identified with optical sources for which the redshift was determined. We use their flux and spectral index measurements along with equation (1) and the correction factor to calculate the total SFR for each galaxy, and we derive a mean SFR $= 1000 \pm 160\ M_\odot$ yr^{-1}. It is clear that the host of GRB 980703 is an average star-forming radio galaxy at $z \approx 1$. This conclusion meshes well with the comparison of the radio spectral index, optical I magnitude, and optical $I-K$ color of the host of GRB 980703 to the same sample (see § 4).

5.2. *Star Formation Rate from Optical and Submillimeter Data*

Djorgovski et al. (1998) used Hα and the 2800 Å UV continuum to calculate an SFR of approximately 10 $M_\odot$ yr^{-1} in the host of GRB 980703, after correcting for rest-frame extinction, $A_V \approx 0.3$ mag. Sokolov et al. (2001) found a similar intrinsic extinction, $A_V \approx 0.3$–0.65, and based on template spectral energy distributions found that the best model for the broadband optical spectrum is given by exponentially decreasing star formation with an extinction-corrected SFR of 20 $M_\odot$ yr^{-1}.

Clearly, the SFR derived from optical indicators is much lower than the value from radio measurements, even after correcting for extinction. This result is part of a general trend that has been observed in galaxies with SFR $\gtrsim 0.1$ $M_\odot$ yr^{-1} (Hopkins et al. 2001). Hopkins et al. (2001) propose dust reddening dependent on SFR as the solution to this problem, and we therefore expect a much better result if we use their prescription. Extending their correlation to SFR$_{1.43} \approx 750\ M_\odot$ yr^{-1}, we find that the predicted observed SFR from Hα is approximately 80 $M_\odot$ yr^{-1}. This value is still much higher than the measured SFR. In fact, in the Hopkins et al. (2001) sample the optically derived SFR rarely exceeds 10 $M_\odot$ yr^{-1}, while the radio-derived values go up to several hundred $M_\odot$ yr^{-1}, indicating that the optical emission does not trace the entire star-forming volume. Thus, the SFR values for this particular galaxy are not unexpected.

The submillimeter (e.g., 350 GHz) emission from galaxies serves as another estimator of SFR, and it is related to the radio emission at 1.43 GHz via a redshift-dependent spectral index, $\beta_{1.4}^{350}$ (Carilli & Yun 1999, 2000; Dunne, Clements, & Eales 2000). Using the value from Carrilli & Yun (2000), $\beta_{1.4}^{350} \approx 0.54 \pm 0.16$ at $z \approx 0.97$, we find $F_\nu(350) \approx 1.3_{-0.8}^{+1.9}$ mJy. Observations with the Submillimeter Common User Bolometer Array (SCUBA) camera on the James Clark Maxwell Telescope 12.4 days after the burst provided a 2 σ upper limit of 3.2 mJy on the combined emission from the afterglow and host at 350 GHz (Smith et al. 1999), consistent with the predictions from the radio-submillimeter relation.

To conclude, we use the derived SFR to calculate the expected far-IR (FIR) emission from the host of GRB 980703. The luminosity of the FIR radiation can be derived from the empirical relation suggested by Helou, Soifer, & Rowan-Robinson (1985),

$$q = -12.6 + \log\left(F_{\rm FIR}/F_{1.4}\right) \approx 2.3 , \qquad (2)$$

which evaluates to $L_{\rm FIR} \approx 1.5 \times 10^{12}\ L_\odot$ for the host of GRB 980703; here, $F_{\rm FIR}$ is the total flux in the range 40–120 μm in units of ergs s^{-1} cm^{-2}, and $F_{1.4}$ is the flux density at 1.4 GHz in units of ergs s^{-1} cm^{-2} Hz^{-1}. This value of the FIR luminosity places the host galaxy of GRB 980703 in the category of ultraluminous infrared galaxies (ULIRGs; Sanders & Mirabel 1996). A similar claim was made for the host galaxy of GRB 970508 (Hanlon et al. 2000); however, the 41″ diameter beam of the *Infrared Space Observatory* (*ISO*) prevents a conclusive association of the detected 60 μm source with the host galaxy.

6. OFFSETS AND SOURCE SIZE

Holland et al. (2001) used a $R^{1/n}$ profile to fit the optical emission from the host and found that the best fit gives a half-light radius of 0″.13, which corresponds to an exponential disk with a scale diameter of 0″.44. Thus, the physical size of the galaxy is $D_{\rm opt} \approx 3.7$ kpc, 30% larger than the upper limit from our radio measurements. Holland et al. (2001) claim that the center of the galaxy is 0.2 mag bluer than the outer regions of the host. If so, star formation must be mainly taking place within the inner parts of the galaxy. Since the radio emission directly traces current star formation, we expect the radio emission to be more centrally concentrated than the optical emission. Thus, as expected, the radio size of the galaxy is smaller than the optical size.

Most likely the GRB is located within the nuclear starburst, given the small offset of the GRB from the centroid of the galaxy. If so, it raises the question of why the afterglow was not completely extinguished by dust. In fact, in order to reconcile the optical- and radio-derived SFRs, we require a rest-frame extinction of $A_V \sim 4.5$ mag. Observations of the afterglow, which provide an estimate of extinction along the line of sight to the burst, give values of 1–2 mag from optical observations and a somewhat higher (but highly uncertain) value from X-ray observations (Bloom et al. 1998; Castro-Tirado et al. 1999; Vreeswijk et al. 1999). Thus, the extinction in the nuclear star-forming region is higher than the average over the whole galaxy, and the correction to the observed optical SFR is almost sufficient to reconcile it with the value of 750 $M_\odot$ yr^{-1} derived from the radio.

The relatively small source size also agrees well with the classification of the host of GRB 980703 as a ULIRG exhibiting a starburst. Kennicutt (1998 and references therein) showed that star formation with a rate $\gtrsim 20\ M_\odot$ yr^{-1} invariably takes place in circumnuclear regions of size 0.2–2 kpc, in the form of nuclear starburst. As a result, we expect that ULIRGs will have such size scales when traced by star formation, and the source size we measured for the host of GRB 980703 indicates that it is probably undergoing a nuclear starburst.

Finally, from the source size and offset measurement we conclude that GRB 980703 took place inside the star-forming region, providing further indirect evidence linking GRBs to massive stars

7. DISCUSSION AND CONCLUSIONS

Late-time observations of GRB 980703 reveal a steady component, with a flux density $F_{\nu,1.43} = 68.0 \pm 6.6\ \mu$Jy and a spectral index $\beta = 0.32 \pm 0.12$. The spectral and temporal characteristics of this emission indicate that it does not arise from the afterglow itself but rather it is the result of star formation in the host galaxy, with SFR $\approx 750\ M_\odot$ yr^{-1}. This leads to the interpretation that this host galaxy is a ULIRG undergoing a starburst. In addition, the star formation is concentrated within the inner 3 kpc of the host, and the progenitor of GRB 980703 was positioned within this region of star formation. This conclusion lends additional support for the collapsar model.

If GRBs really come from massive stars, then they can be used to trace the star formation history of the universe (e.g., Wijers et al. 1998). In addition, GRBs and their afterglows are potentially detectable out to very high redshifts (Lamb & Reichart 2000). These propositions, taken together with the dust-penetrating power of their γ-ray emission, make GRBs a unique tool for the study of galaxies and the intergalactic medium over a wide redshift range. In particular, radio and submillimeter/FIR observations of a GRB-selected galaxy sample will be extremely useful for the study of the obscured star formation fraction and the properties of starbursts at high redshifts. Moreover, a comparison of the global star formation history as derived from these long-wavelength host studies, with the redshift distribution of GRBs, will provide valuable insight as to how well GRBs trace the formation rate of massive stars (e.g., Blain & Natarajan 2000); we expect that if GRBs trace only a particular channel of star formation, the two distributions will not agree.

Therefore, it is imperative to study the hosts of GRBs in the radio and submillimeter/FIR. Future observatories such as the *Space Infrared Telescope Facility* (*SIRTF*; to be launched in 2002 July), the Atacama Large Millimeter Array (ALMA), the Expanded VLA (EVLA), and the Square Kilometer Array (SKA) will allow detailed studies of these hosts. In the FIR, *SIRTF* will have the ability to detect sources down to several mJy, allowing the detection of galaxies with SFRs comparable to that in the host of GRB 980703 out to $z \sim$ few; alternatively, we will be able to detect hosts with SFRs as low as a few tens of $M_\odot$ yr^{-1} at $z \sim 1$. ALMA has a projected sensitivity ranging from a few

μJy at 35 GHz to $\sim$1 mJy at 850 GHz for a 10 minute observation, improving on the capability of an instrument such as SCUBA by almost 2 orders of magnitude. Combined with an expected resolution of approximately 1″, ALMA will provide an unprecedented ability to study GRB host galaxies over a very wide redshift, SFR, and frequency range. The EVLA and SKA will greatly improve the detectability of host galaxies in the radio and will also allow much higher angular resolution studies of compact star-forming regions. With a factor 10 increase in resolution and a factor 5 increase in sensitivity over the current VLA, we will be able to probe scales of approximately 5 mas with the EVLA; for a galaxy at $z \approx 1$ this translates to a physical scale of 150 pc. In addition, EVLA will detect galaxies with a total SFR as low as 50 $M_{\odot}$ yr^{-1} at $z \sim 1$. The SKA, with a similar resolution but a much larger collecting area, will extend this capability to even lower SFRs and smaller star-forming regions.

Thus, as more host galaxies are detected and studied in detail in the radio and submillimeter/FIR, we will be able to address a large number of issues pertaining not only to the bursts themselves but also to the characteristics of galaxies at high redshifts.

We acknowledge support by NSF and NASA grants. S. R. K. thanks Brian McBreen for useful comments on the *ISO* observations of GRB 970508. We thank Mike Garrett for pointing out an error in our determination of the luminosity distance.

REFERENCES

Barger, A. J., Cowie, L. L., & Richards, E. A. 2000, AJ, 119, 2092
Blain, A. W., & Natarajan, P. 2000, MNRAS, 312, L35
Bloom, J. S., et al. 1998, ApJ, 508, L21
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2001, submitted to AJ (astro-ph/0010176)
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
———. 2000, ApJ, 530, 618
Castro-Tirado, A. J., et al. 1999, ApJ, 511, L85
Chevalier, R. A., & Li, Z. 2000, ApJ, 536, 195
Condon, J. J. 1992, ARA&A, 30, 575
Djorgovski, S. G., et al. 1998, ApJ, 508, L17
Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., Bloom, J. S., Odewahn, S. C., & Diercks, A. 2001, ApJ, in press
Dressler, A., & Gunn, J. E. 1982, ApJ, 263, 533
Dunne, L., Clements, D. L., & Eales, S. A. 2000, MNRAS, 319, 813
Falcke, H., Lehar, J., Barvainis, R., Nagar, N. M., & Wilson, A. S. 2001, in ASP Conf. Ser. 224, Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring, ed. B. M. Peterson, R. S. Polidan, & R. W. Pogge (San Francisco: ASP), 265
Fomalont, E. B., et al. 1991, AJ, 102, 1258
Frail, D. A., Waxman, E., & Kulkarni, S. R. 2000, ApJ, 537, 191
Galama, T. J., & Wijers, R. A. M. J. 2001, ApJ, 549, L209
Haarsma, D. B., et al. 2000, ApJ, 544, 641
Hanlon, L., et al. 2000, A&A, 359, 941
Helou, G., Soifer, B. T., & Rowan-Robinson, M. 1985, ApJ, 298, L7
Holland, S., et al. 2001, A&A, 371, 52
Hopkins, A. M., Connolly, A. J., Haarsma, D. B., & Cram, L. E. 2001, AJ, 122, 288
Ivison, R. J., et al. 2000, MNRAS, 315, 209
Kennicutt, R. C., Jr. 1992, ApJ, 388, 310
———. 1998, ARA&A, 36, 189
Lamb, D. Q., & Reichart, D. E. 2000, ApJ, 536, 1
Richards, E. A. 2000, PASP, 112, 1001
Richards, E. A., et al. 1999, ApJ, 526, L73
Rola, C. S., Terlevich, E., & Terlevich, R. J. 1997, MNRAS, 289, 419
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Smith, I. A., et al. 1999, A&A, 347, 92
Sokolov, V. V., et al. 2001, A&A, 372, 438
Vreeswijk, P. M., et al. 1999, ApJ, 523, 171
Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P. 1998, MNRAS, 294, L13
Windhorst, R. A., et al. 1993, ApJ, 405, 498