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A SEARCH FOR OPTICAL AFTERGLOW FROM GRB 970828

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ABSTRACT

We report on the results of *R*-band observations of the error box of the γ-ray burst of 1997 August 28 made between 4 hr and 8 days after this burst occurred. No counterpart was found varying by more than 0.2 mag down to $R = 23.8$. We discuss the consequences of this nondetection for relativistic blast wave models of γ-ray bursts and the possible effect of redshift on the relation between optical absorption and the low-energy cutoff in the X-ray afterglow spectrum.

Subject headings: dust, extinction — galaxies: general — gamma rays: bursts — gamma rays: observations — radiation mechanisms: nonthermal

1. INTRODUCTION

Since the first discovery of a γ-ray burst (GRB) in 1967 (Klebesabel et al. 1973), these short outbursts of highly energetic photons have formed one of astronomy's most elusive problems. Following the discovery by Meegan et al. (1992) of their isotropic sky distribution and inhomogeneous spatial distribution (which excluded that GRBs originate from a galactic disk source population) the discussion on the nature of GRB sources focused on their distances: either of order 10^5 pc (galactic halo model) or several Gpc (cosmological model). The association of the optical counterpart of GRB 970228 (Groot et al. 1997a; van Paradijs et al. 1997) with what is most likely a galaxy (Groot et al. 1997b; Metzger et al. 1997a; Sahu et al. 1997a) and especially the determination of a redshift for GRB 970508 (Metzger et al. 1997b) have shown that GRBs are located at cosmological distances and are thereby the most luminous photon sources known in the universe. The question of what causes GRBs has now become the center of the discussion, and the detection of more optical counterparts is a key element in determining their cause.

In this Letter we report on our search for a transient optical counterpart for GRB 970828, based on observations made with the 4.2 m William Herschel Telescope (WHT) on La Palma and the 3.5 m WIYN Telescope on Kitt Peak. No counterpart was detected, down to a magnitude level $R = 23.8$.

GRB 970828 was discovered with the All-Sky Monitor (ASM) on the *Rossi X-Ray Timing Explorer* (*RXTE*) on 1997 August 28 $17^h44^m36^s$ UT from an elliptical region centered at R.A. $= 18^h08^m29^s$, decl. $= +59°18'.0$ (J2000), with a major axis of $5'.0$ and a minor axis of $2'.0$ (Remillard et al. 1997; Smith et al. 1997). Within 3.6 hr the *RXTE*/PCA scanned the region of the sky around the error box of the ASM burst and detected a weak X-ray source, located in the ASM error box with a 2–10 keV flux of 0.5 mcrab (Marshall et al. 1997). The burst was also detected with the Burst and Transient Source Experiment (BATSE) and the GRB experiment on *Ulysses.* Its fluence and peak flux were 7×10^{-5} ergs cm^{-2} and 3×10^{-6} ergs cm^{-2} s^{-1}, respectively. From the difference between burst arrival times, its position was constrained to lie within a $1'.62$ wide annulus, that intersected the *RXTE* error box (Hurley et al. 1997). In an *ASCA* observation made between August 29.91 and 30.85 UT, a weak X-ray source was detected at an average flux level of 4×10^{-13} ergs cm^{-2} s^{-1} (2–10 keV). The *ASCA* error box is centered on R.A. $= 18^h08^m32^s.3$, decl. $= +59°18'54''$(J2000) and has a $0'.5$ radius (Murakami et al. 1997).

2. OBSERVATIONS AND DATA ANALYSIS

We observed the GRB error box with the Prime Focus Camera of the WHT on nine nights between August 28, 21^h47^m UT, and September 5, 22^h07^m UT (see Table 1). The first observation was made just over 4 hr after the γ-ray burst. All observations were made with a Cousins *R*-band filter (Bessell 1979). During the first two nights and the last three nights, we used a LORAL 2048×2048 CCD chip, with 15 μm pixels, giving a field of view of $8'.45 \times 8'.45$. During the intervening nights we used an EEV CCD chip (2048×4096), windowed at 2048×2400, with 13.5 μm pixels, giving a $8'.1 \times 9'.5$ field of view. On August 30 two *R*-band images were made with the WIYN Telescope. The camera contained a 2048×2048 CCD, giving a field of view of $6'.8 \times 6'.8$.

We obtained a photometric calibration of the CCD images from observations of Landolt Selected Area 113, stars 281,

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TABLE 1
LOG OF OBSERVATIONS OF GRB 970828

Date	Telescope	Start (UT)	Exposure Time (s)	Seeing
Aug 28	WHT	21:47	900	0".86
Aug 29	WHT	21:15	900	0".74
Aug 30	WIYN	05:08	600	0".8
Aug 30	WIYN	07:38	900	1".2
Aug 30	WHT	23:22	900	0".90
Aug 31	WHT	20:54	900	0".71
Sep 1	WHT	21:16	600	0".80
Sep 2	WHT	20:53	600	0".76
Sep 3	WHT	22:44	600	0".88
Sep 4	WHT	21:53	600	0".79
Sep 5	WHT	22:07	600	0".86

158, 183, and 167 (Landolt 1992), on August 31, 0^h14^m UT with the WHT.

A region of $2' \times 2'$ centered on the *ASCA* position in the bias-subtracted and flat-fielded images was analyzed using DoPhot (Schechter, Mateo, & Saha 1993), in which astrometric and photometric information of all objects are determined from bivariate Gaussian function fits to the brightness distribution in their image; the parameters of these fits also tell us whether an object is stellar (i.e., unresolved) or a galaxy. In this region (see Fig. 1) we find a total of 63 objects, 36 of which are stellar and 27 galaxies, down to $R = 23.8$.

We have searched for variable objects by comparing the magnitudes of each star as determined for each of the images. Comparison of images taken on different nights showed no variation on timescales between 1 day and 1 week in excess of 0.2 mag for $R \leq 23.8$ (for the last three nights the limit on variability is 0.3 mag for $R \leq 23.8$). Comparison of three images taken on the night of August 29–30 showed no variations on timescales of several hours in excess of 0.2 mag for $R < 22.5$.

3. DISCUSSION

3.1. *Comparison with Optical Afterglows of GRB 970228 and GRB 970508*

The large variation in optical response of GRBs (relative to their strength in γ-rays) was already clear from a comparison of GRB 970228 and GRB 970111. Within 1 day after GRB 970228 occurred it showed an optical afterglow at $R = 20.8$ (van Paradijs et al. 1997; Galama et al. 1997a; Pedichini et al. 1997; A. Guarneri et al. 1997, private communication). GRB 970111 was not detected in optical observations made 19 hr after it occurred ($R > 20.8$ and $R > 22.6$, for variations in excess of 0.2 and 0.5 mag, respectively; Castro-Tirado et al. 1997), in spite of the fact that its γ-ray fluence (Galama et al. 1997b) was 5 times larger than that of GRB 970228 (Costa et al. 1997). Since only one deep image was made in the week following GRB 970111, its nondetection may have been the result of, e.g., a very rapid decay of any optical afterglow or a very slow rise thereof (like for GRB 970508; see Bond 1997; Djorgovski et al. 1997; Sahu et al. 1997b; Galama et al. 1998).

The nondetection ($R > 23.8$ for variations in excess of 0.2 mag) of GRB 970828 during our optical observations, which covered the time interval between 4 hr and 8 days after the burst at intervals of 1 day, show the very large range in optical responses of GRBs in an even more striking fashion. We have used the fluence, E_{GRB} (in ergs cm^{-2}), as a measure of the GRB strength and compared the ratio of the optical peak flux to the GRB fluence of GRB 970828 with that of GRB 970508. The latter had a peak magnitude $R = 19.8$ (Mignoli et al. 1997);
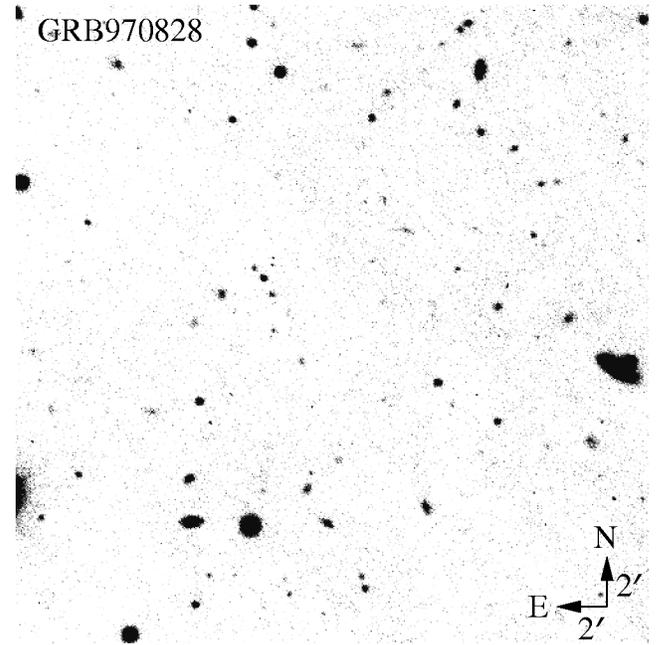
FIG. 1.—$2' \times 2'$ *R*-band image of the sky region centered on the 0".5 radius *ASCA* error box of GRB 970828, taken at the WHT on September 2.

therefore, the difference in optical peak luminosities between GRB 970508 and GRB 970828 is more than 4 mag. The ratio of their fluences is $E_{GRB}(970828)/E_{GRB}(970508) = 24$ (Kouveliotou et al. 1997). Thus, we find that the optical peak response of GRB 970828, with respect to its γ-ray fluence, is a factor $\sim 10^3$ smaller than that of GRB 970508. (Compared to GRB 970228, the difference is a factor of more than 10^2.)

We have made a similar comparison with published X-ray afterglow fluxes (F_X) for the two GRBs with optical afterglow. Most of these refer to the energy range 2–10 keV. Only the *ROSAT* fluxes had to be transformed to this range; in doing this we assumed a power-law X-ray spectrum with photon index in the range -1.4 to -2.0 (Costa et al. 1997; Yoshida et al. 1997). This range leads to an uncertainty in the transformed *ROSAT* flux of less than a factor 2. The results, in the form of the ratio $\mathscr{R}_X = F_X/E_{GRB}$, are summarized in Figure 2, which shows the variation of this quantity as a function of the time interval since the burst, for three bursts with published X-ray afterglow information. This figure shows that the differences in $\mathscr{R}_X$ between these bursts are moderate (less than an order of magnitude). It is noteworthy that the two bursts with optical counterparts also have the highest values of $\mathscr{R}_X$ (for a given value of Δt).

We finally compared the peak flux in the *R*-band afterglows with the brightness of the X-ray afterglow. In view of their rather similar decay rates, we used for the latter the 2–10 keV flux as measured 1 day after the GRB occurred, $F_X(1\ \mathrm{day})$. The corresponding ratio $F_{peak}(R\ \mathrm{band})/F_X(1\ \mathrm{day})$ for GRB 970828 differs by a factor of more than 150 from that for GRB 970508, and a factor of more than 10 from that for GRB 970228.

3.2. *Comparison with Relativistic Blast Wave Models*

A relatively successful way of explaining the existence of GRB afterglows (at all wavelengths) has been the so-called blast wave or fireball models (e.g., Mészáros 1995). These models involve the generation of a massive amount of energy
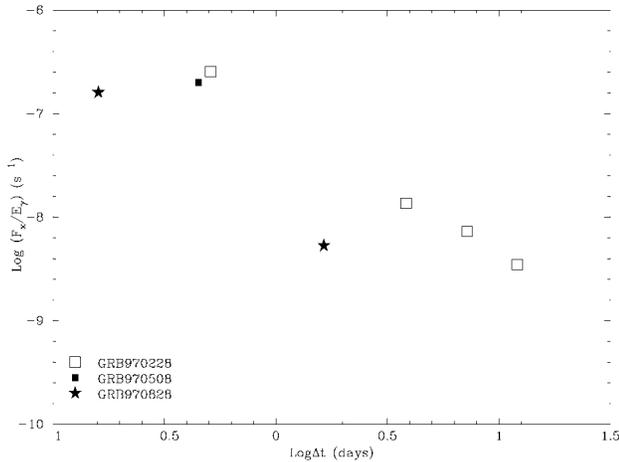
FIG. 2.—Variation of the ratio R_X of the afterglow (2–10 keV) X-ray flux (see text) to the fluence in the γ-ray burst as function of time in days. GRB fluences were obtained from the following sources. GRB 970228, Costa et al. (1997); GRB 970508, Kouveliotou et al. (1997); GRB 970828, Kouveliotou (1997, private communication). The X-ray fluxes were obtained from the following sources, GRB 970228, Costa et al. (1997), Yoshida et al. (1997), Frontera et al. (1997); GRB 970508, Piro et al. (1997); GRB 970828, Marshall et al. (1997), Murakami et al. (1997).

FIG. 3.—Variation of the observed fluxes in γ-rays, X-rays, and in the B and R bands of GRB 970828, together with simple blast wave model fits as described in Wijers et al. (1997).

in a very small, compact region by an unexplained mechanism. The result of this dumping of energy is a relativistically expanding fireball (blast wave), that collides with the interstellar or circumstellar medium and generates shocks that emit the synchrotron radiation that is observed as the afterglow.

Figure 3 shows the available data for GRB 970828 in γ-rays, X-rays, B, and R, plus simple blast wave model fits, which are normalized to agree with the X-ray data. If we compare this with the data available for GRB 970228 (Wijers, Rees, & Mészáros 1997), it is striking that the decay part of the X-ray curves are virtually the same for these two bursts (i.e., in slope *and* offset). But whereas the first stages of the optical decay for GRB 970228 are in good agreement with the afterglow prediction (Wijers et al. 1997), the earliest upper limit to the optical brightness of GRB 970828 is 300 times lower than the predicted value.

The simplest spherically symmetric blast wave models for GRB afterglows require that the slope of the spectrum follows from the slope of the temporal decay, once the decay curve is measured in one wavelength band and is found to be a pure power law. From that, the offset in brightness at any other waveband is fixed and the predicted flux at that waveband is hard to change. Mészáros, Rees, & Wijers (1998) showed that if the blast wave is beamed, one can get different relations between spectral and temporal slopes, giving possibly much smaller offsets between the optical and X-ray light curves of the afterglow. As an example, let the energy per unit solid angle, E, vary with angle from the jet axis, θ, as $E \propto \theta^{-4}$ and the Lorentz factor $\Gamma \propto \theta^{-1}$. Then a temporal decay rate $F \propto t^{-1.3}$ as seen here would occur for a spectrum $F_\nu \propto \nu^{0.4}$, i.e., it would rise from optical to X-rays and the predicted R-band curve would be a factor 24 below the X-ray curve. At the time of our first limit this model would give $R = 28.4$, quite consistent with the data.

3.3. *Absorption in Redshifted Material*

Another explanation, pointed out to us by B. Paczyński, for the nondetection of optical afterglow could be photoelectric
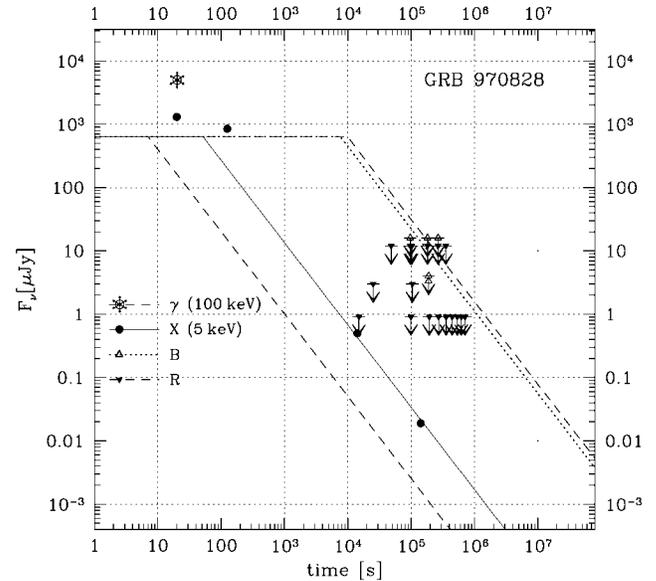
absorption, also visible as a low-energy cutoff in the X-ray spectrum. If we assume a modest hydrogen column density of $N_H \sim 10^{21}$ atoms cm^{-2} and make the assumption that the absorbing material is at redshift $z = 0$, this would imply 0.34 mag of extinction in the R band (Gorenstein 1975; Cardelli, Clayton, & Mathis 1989).

In case the absorption takes place at some redshift z the effect is a bit more complicated. The cross section for photoelectric absorption in the (0.2–5) keV range depends on energy roughly as $E^{-2.6}$ (Morrison & McCammon 1983). Then the factor by which the apparent N_H, inferred from the low-energy cutoff in the X-ray spectrum, has to be increased is approximately $(1 + z)^{2.6}$. If we assume, for example, that the GRB occurred at a redshift of $z = 1$, the factor by which the apparent value of N_H has to be increased would be ~ 6. Moreover, the photons in the R band we observe would be at wavelengths near 3200 Å at the source, at which wavelength the interstellar absorption is approximately a factor 2.5 larger than in the R band (Cardelli et al. 1989). These combined effects would lead, for a GRB at $z = 1$ and an apparent, moderate, $N_H = 10^{21}$ atoms cm^{-2}, to an R-band extinction of ~ 5 mag.

If absorption is the correct explanation, a substantial fraction of GRB sources (those with a very small optical response) would be located close to where large column densities are available, i.e., in disks of galaxies. This would link GRBs to a population of massive stars. This is expected for the failed-supernova model and for the hypernova model, proposed by Woosley (1993) and Paczyński (1998), respectively. In view of the large kick velocities imparted on neutron stars at birth (Lyne & Lorimer 1994; Hansen & Phinney 1997; van den Heuvel & van Paradijs 1997) it remains to be seen whether a merging neutron star binary model would be consistent with this consequence.

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