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CANDIDATES FOR A GAMMA-RAY BURSTER OPTICAL COUNTERPART[1]

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ABSTRACT

The small size of the 1928 optical error box for the 1978 November 19 gamma-ray burster (GRB) allows for a very deep search for the quiescent optical counterpart. We have used a CCD camera on the Cerro Tololo Inter-American Observatory 4 m telescope to search this field to a m_B fainter than 25.0. We find several objects in the 1928 error box, including one which varies by over 1 mag on a time scale of under a day. This variable object corresponds in position to object A of Pedersen *et al.* Since we confirm that their object B has disappeared, there are two faint variables in the field. It is currently unclear which one (if either) of the variables is the true GRB counterpart. We also report astrometry and U, B, V, and r photometry for eight nearby comparison stars.

Subject heading: gamma rays: bursts

I. INTRODUCTION

The discovery of optical counterparts for gamma-ray bursters (GRBs) has long had a high priority in GRB research. Accurate GRB positions on the sky have been determined so as to allow searches for counterparts. In most cases, no interesting optical, radio, or X-ray sources can be related to the GRB phenomenon. A typical GRB error region will be empty of optical sources down to the limit of the Palomar Sky Survey. Two important exceptions to this rule have been found. The first concerns the highly unusual GRB seen on 1979 March 5 (Cline 1982). The direction to this GRB is the same as that to a supernova remnant in the Large Magellanic Cloud. It is still controversial whether this is only a coincidence and the burster is much closer than 55 kpc. The other important exception is the GRB seen on 1978 November 19 (Cline *et al.* 1981). Schaefer (1981) found an optical transient associated with the GRB on an archival photograph from 1928.

The region near the 1978 November 19 GRB has been extensively searched for a quiescent counterpart at a variety of wavelengths. Null reports on radio and infrared counterparts are given by Hjellming and Ewald (1981) and Schaefer and Ricker (1983). A faint X-ray source has been reported by Grindlay *et al.* (1982). On the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope B and V plates taken by M. H. Liller (Schaefer and Ricker 1983), an optical variable was suspected of being visible, but this possible source was not detected in subsequent deeper searches. Pedersen *et al.* (1982), Pedersen and Motch (1982), and Pederson *et al.* (1983) located faint objects in the 1928 optical error box. Most intriguing of these is their source B which disappeared sometime between 1982 July and September.

The small size (8″ × 18″) of the 1928 optical error box offers a unique opportunity to perform a very deep search for a GRB quiescent counterpart. It is possible that proper motion could move the counterpart out of the error box since 1928. For a distance of 100 pc, a transverse velocity of 100 km s^{-1} will cause an 11″ shift in position, which is comparable to the size of the error box. We observed this region with a CCD camera on the CTIO 4 m telescope on four nights in October 1982. We detect several faint sources inside the 1928 error box. One of these sources is a large-amplitude variable which changes on a time scale of under 1 day.

II. OBSERVATIONS

Data were obtained with the prime focus CCD camera on the CTIO 4 m telescope. This instrument uses an RCA thinned, backside-illuminated chip with a field of view of 5′ × 3′ (E-W by N-S). Each pixel is 0″.6 square. A log of our observations is presented in Table 1. We obtained over 8 hours of exposure (primarily through the B and V filters) on the 1928 error box. Standard CTIO procedures were used to remove bias, flat field, and defringe each raw data frame before any additional

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TABLE 1

JOURNAL OF OBSERVATIONS

DATE (1982)	UT Start	UT End	FILTER	EXPOSURE (minutes)	FWHM OF SEEING DISK (arcsec)	COMMENTS
Oct 19 ...	6:33	6:43	*B*	10	1.4	
Oct 20 ...	2:17	2:37	*B*	20	1.8	
	2:48	3:08	*V*	20	1.7	
	3:11	3:31	*B*	20	2.1	high thin clouds
Oct 22 ...	1:14	1:59	RG 1000	40	2.3	two 20 min frames co-added
	2:12	2:52	*r*	40	2.7	two 20 min frames co-added
	3:15	3:45	*B*	30	2.6	
	3:47	4:52	*V*	60	2.6	four 15 min frames co-added
	4:57	5:27	*B*	30	2.7	ESO obs. 4:51–7:13 UT[a]
Oct 23 ...	1:12	2:25	*U*	40	2.7	two 20 min frames co-added, clouds
	2:38	3:08	*B*	30	2.4	ESO obs. 1:39–6:31 UT[a]
	3:09	4:36	*V*	60	1.9	four 15 min frames co-added
	4:40	5:41	*B*	60	2.0	two 30 min frames co-added
	5:43	6:14	*V*	30	1.9	two 15 min frames co-added

[a] Pedersen *et al.* (1983).

analysis was done. After each exposure, the telescope position was shifted by 10 to 15 pixels to minimize the possibility of low-level artifacts in chip response affecting the observations. Individual frames were registered by shifting an integral number of pixels (without interpolation) before co-adding.

Magnitudes and precise positions were determined using Butcher's aperture photometry code (described in Adams *et al.* 1980). This program uses the first intensity moments to determine the object center, and sums up the intensity within a 2 pixel radius of the center to produce a magnitude value. On frames analyzed at CTIO, we first smoothed the data with a 2 by 2 resolution to reduce the noise. This is a valid procedure because our pixel size oversamples the seeing disk. The zero points for the Johnson *UBV* system were fixed by stars 10, 11, and 12 of Fishman, Duthie, and Dufour (1981). The zero point for the Gunn *r* filter (Thuan and Gunn 1976) is set by the measurement of object Q by Pedersen *et al.* (1983).

The quoted error in the magnitude is based on (1) Poisson statistics of the detected photons, (2) error in the sky level, and (3) noise introduced by the sky within the summing aperture. These errors were checked by computing magnitudes for stars in frames of the same field taken on the same night, and comparing this dispersion with the error value returned by the program. The two agree to within the statistical uncertainty.

Table 2 gives magnitudes and colors for five additional objects in the CCD field (but not in the error box) which may be useful as secondary standards. Errors in all cases are typically 0.03 in *V* and 0.04 in each color.

We also measured accurate astrometric positions for seven comparison stars near the 1928 error box. The positions of these stars and from seven to fourteen nearby SAO stars were measured with a Mann measuring engine on the Palomar Sky Survey blue print, a CTIO 4 m *V* plate, and twice for the European Southern Observatory (ESO) deep blue survey glass plate. The positions for the seven stars were calculated using a six-parameter fit. The four positions for each star were then averaged, and the results are presented in Table 3.

We found evidence for three objects:

1. On the night of 1982 October 22, we found a $m_v = 23.7$ object (designated AA) near the center of the

TABLE 2

PHOTOMETRY OF COMPARISON STARS

Designation (Ref.)	*U*	*B*	*V*	*r*
10 (1)	13.77[a]	13.46[a]	12.74[a]	...
11 (1)	19.91[a]	18.77[a]	17.13[a]	15.49
12 (1)	16.02[a]	15.86[a]	15.13[a]	...
QSO (2)	19.34	20.16	19.68	18.94
Q (3)	...	23.72	22.88	21.32[b]
XX (4)	21.35	22.08	21.37	20.36
YY (4)	21.42	20.88	19.66	18.37
ZZ (4)	19.21	19.52	18.79	...

[a] Magnitudes taken from Fishman, Duthie, and Dufour 1981.

[b] Magnitude taken from Pedersen *et al.* 1983.

REFERENCES.—(1) Fishman, Duthie, and Dufour 1981; (2) Pedersen *et al.* 1983; (3) Hjellming and Ewald 1981; (4) see Table 4.

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TABLE 3

ASTROMETRY OF COMPARISON STARS

Designation (Ref.)	R.A. (1950)	Decl. (1950)
10 (1)	$1^{h}16^{m}31^{s}.152 \pm 0^{s}.04$	$-28°50'45''.15 \pm 0''.3$
11 (1)	1 16 26.284 ± 0.04	−28 50 31.53 ± 0.3
12 (1)	1 16 27.496 ± 0.04	−28 49 56.76 ± 0.3
QSO (2)	1 16 26.040 ± 0.04	−28 51 31.55 ± 0.3
XX (3)	1 16 25.337 ± 0.08	−28 50 51.46 ± 0.6
YY (3)	1 16 29.148 ± 0.04	−28 51 15.38 ± 0.3
ZZ (3)	1 16 28.379 ± 0.08	−28 49 57.53 ± 0.6

REFERENCES.—(1) Fishman, Duthie, and Dufour 1981; (2) Pedersen *et al.* 1983; (3) this *Letter*.

TABLE 5

ASTROMETRY OF OBJECTS IN THE 1928 ERROR BOX

Designation	R.A. (1950)	Decl. (1950)
AA	$1^{h}16^{m}25^{s}.696 \pm 0^{s}.034$	$-28°51'1''.38 \pm 0''.4$
CC	1 16 25.796 ± 0.034	−28 50 58.78 ± 0.4
DD	1 16 25.406 ± 0.034	−28 51 2.28 ± 0.4

1928 error region (see Fig. 1, Plate L6). This object was invisible two nights earlier and one night later (see Fig. 2, Plate L6).

2. Several arc seconds to the northeast of the variable object AA was a faint source designated CC. This object is faintly visible in both Figures 1 and 2. When we separately add all our *B* and *V* frames together, object CC is detected in both colors at the 3 σ confidence level.

3. At 4″ to the east of the variable source was a blue object designated DD. This possible object is detected only at 3 σ when all our *B* frames are co-added together.

Our photometry of these three objects is presented in Table 4. The quoted error bars are for 1 standard deviation, and the significance of each detection is included in parentheses.

We are highly confident that the detection and variability of source AA are not artifacts of the instrument or data analysis. The variable object was detected at the 8 σ confidence level in the 2 × 2 smoothed *V* frames from October 22. The source was visible on each of the four *V* frames with no apparent variability. Since the telescope was repositioned between frames, it is unlikely that a cosmic ray or bad pixel could mimic the observations. The image profile of AA is a Gaussian of the same width as nearby stars. AA was seen independently in the *B* and *r* data from the same night at a lower confidence level (3 and 4 σ respectively). For these reasons, we have confidence that we detected a true celestial object on October 22. For similar reasons, we are confident that this object was significantly fainter on our other nights of observation. The detection of source CC in two colors gives us confidence in its reality. Source DD requires confirmation.

We have determined the accurate astrometric positions of our three sources (see Table 5). Our CCD frames do not include the positions of any SAO stars, but they do include the positions of the seven stars with astrometric positions listed in Table 3. These seven stars were used to determine the plate scale and rotation angle from the north-south orientation. The values for these two parameters were found to be not significantly different from the nominal values of $0''.60$ per pixel and 0.0 degrees respectively. From repeated measures of the distances between pairs of stars on many frames with different exposures and filters, we found that the relative star positions can be determined to $0''.3$. The position of AA was found from the *V* filter observations on October 22. On this frame, only the positions of stars 11, QSO, and YY were used, as the other stars were either saturated or confused. The positions quoted in Table 5 are with respect to these three stars. The position of AA is $1^{s}.461 \pm 0^{s}.023$ west of and $4''.77 \pm 0''.3$ north of the centroid of the three standard stars.

III. DISCUSSION

Pedersen *et al.* (1983) report the positions for their objects A and B as well as for the same three compari-

TABLE 4

PHOTOMETRY OF OBJECTS IN THE 1928 ERROR BOX

Designation	B[a]	V[b]	r[c]	$B - V$
AA (variable):				
Oct 22...........	24.9 ± 0.3 (3 σ)	23.7 ± 0.1 (8 σ)[d]	22.0 ± 0.3 (4 σ)[d]	1.2 ± 0.3
Oct 19, 20, 23 ...	> 25.9 (3 σ)	> 25.4 (3 σ)	...	...
CC (faint)	25.8 ± 0.3 (3 σ)	25.4 ± 0.3 (3 σ)	22.2 ± 0.3 (3 σ)[d]	0.4 ± 0.4
DD (blue)	25.9 ± 0.3 (3 σ)	> 25.4 (3 σ)	> 22.2 (3 σ)	≲ 0.0

[a] 200 minutes of exposure (60 minutes on Oct 22).
[b] 170 minutes of exposure (60 minutes on Oct 22).
[c] 40 minutes of exposure.
[d] Data were smoothed as described in text.

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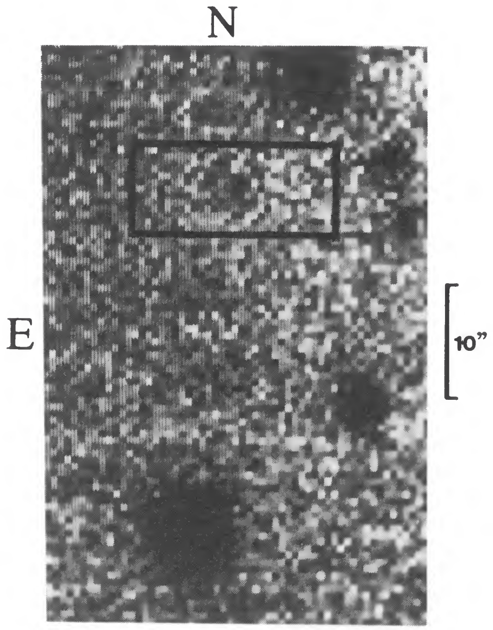

FIG. 1.—The variable object AA on 1982 October 22. Near the center of the 1928 optical error box (shown as a rectangle) is an 8 σ source. Note that it is somewhat brighter than the star roughly 10″ to the SSE. This picture is a composite of four 15 minute exposures through a *V* filter.

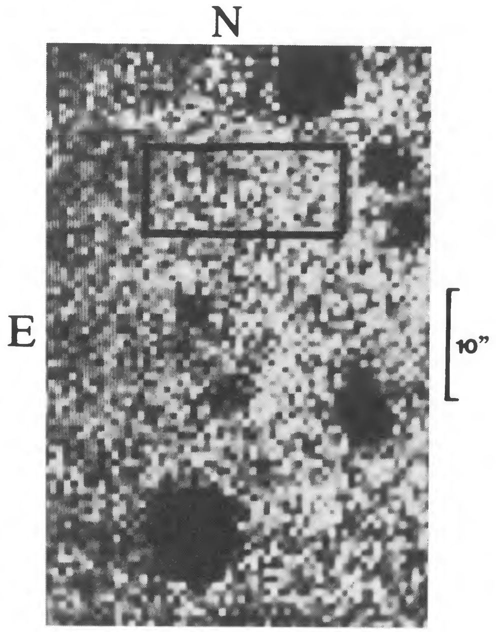

FIG. 2.—The variable object AA in its "down state." The position of the variable object is empty on this composite of *V* frames from 1982 October 22 and 23. Note that the variable object is substantially fainter than the star roughly 10″ to the SSE of the error region's center. The darker area in the upper left of the error region is the faint source CC. The QSO appears at the bottom of the picture and the object XX is at the top.

SCHAEFER, SEITZER, AND BRADT (*see* page L51) son stars: object A is $1^{\mathrm{s}}.43 \pm 0^{\mathrm{s}}.05$ west of and $5''.3 \pm 0''.7$ north of the centroid of the three comparison stars. On this basis, our variable object AA appears to be coincident with their object A, *not* with their variable object B. Pedersen *et al.* (1983) also observed object A = AA on October 22 and 23 and noted a suggestion that A = AA was brighter on October 22 by an R-magnitude of 0.7 ± 0.6. We do not detect their source B, but this is consistent with the fact that Pedersen and Motch (1982) and Pedersen *et al.* (1983) report B to have disappeared between July and September of 1982.

The presence of four objects (A = AA, B, CC, and DD) in the small 1928 error box is surprising. To a limit of $m_B = 26.0$, Bahcall and Soniera (1980) predict 0.070 galactic stars in the error box, while Tyson and Jarvis (1979) predict 1.2 extragalactic objects. With three of the four reported objects as either variable or blue, we are now in the unhappy (?) situation of having too many candidates.

It is possible that only one of the variable sources (either AA = A or B) is the true counterpart. A ready explanation for the optical variability is that the accretion rate onto a neutron star in the system changes on short time scales. This changing accretion rate was mentioned as a possibility (Schaefer 1981) in connection with the observed X-ray flux (Grindlay *et al.* 1982). If one of the variable sources is the true counterpart, then its average apparent magnitude must be roughly 25 mag (see Table 4 and Pedersen *et al.* 1983). On the assumption that GRBs are galactic, a reasonable distance estimate is between 30 pc and 300 pc, which implies an absolute magnitude for the GRB system of $M_v = 20$ mag. Since the neutron star most likely has a companion to explain the 1928 optical flux (Schaefer and Ricker 1983), the list of possible companions includes accretion disks, large planets, and white dwarfs. If, instead, the burster were placed at a reasonable upper limit on the distance of 1 kpc, it would still be possible to have a low-mass ($0.1\ M_{\odot}$) and faint ($M_v = 15$ mag) stellar companion.

Another possibility is that neither of the variable sources is the true counterpart. This raises the question of why there are two large-amplitude variables in such a small box. It could be that a large fraction of the objects around 25 mag are variable. Hawkins (1983) finds that the fraction of objects which are variable increases toward fainter magnitudes (10^{-4} at $B = 19$ and 10^{-3} at $B = 21$). If neither variable is the true counterpart, then the apparent magnitude must be fainter than for the case considered in the preceding paragraph. This would increase the likelihood that the GRB consists of a lone neutron star. A lone thermal neutron star is predicted (Helfand, Chanan, and Novick 1980) to have $M > 23$ mag, provided the neutron star was not formed recently. We expect a lone neutron star to be blue in color, much like object DD and not like AA. The blue color of DD may be more suggestive that it is a background quasar rather than a neutron star. The lone neutron star hypothesis has difficulty accounting for the origin of the optical radiation from the 1928 burst (Schaefer and Ricker 1983). In addition, for reasonable distances and ages, the X-ray luminosity of a lone thermal neutron star (Helfand, Chanan, and Novick 1980) is many orders of magnitude smaller than the X-ray source of Grindlay *et al.* (1982).

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