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OPTICAL CANDIDATES FOR THE 1978 NOVEMBER 19 GAMMA-RAY BURST SOURCE[1]

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ABSTRACT

We report on the detection and variability of two very faint ($m_R \sim 24$) objects in the $4'' \times 16''$ error region of the 1928 November 17 optical transient that may be associated with the 1978 November 19 gamma-ray burst source. We discuss the consequences if one of these two objects is the optical counterpart of the gamma-ray burst source. It is possible that, in the ~ 54 years since the 1928 transient, the source has moved out of the 1928 error region. To investigate this possibility, we have made proper motion measurements of objects as faint as $m_R \sim 22$.

Subject headings: gamma rays: bursts — radio sources: general — X-rays: sources

I. INTRODUCTION

The error box for the gamma-ray burst of 1978 November 19 is ~ 10 arcmin^2 (Cline *et al.* 1981). Studies of other small gamma-ray burst error boxes have so far led only to the association of the unusual 1979 March 5 event with the supernova remnant N49 in the LMC (Cline *et al.* 1982). The association has been questioned (see, e.g., Helfand and Long 1979; Zdziarski 1982).

Within the error box of the 1978 November 19 gamma-ray burst event, Hjellming and Ewald (1981) found three pointlike radio sources and one just outside the error box. One marginal detection (3.5 σ level of confidence) of an X-ray source, was reported by Pizzichini *et al.* (1981) and Grindlay *et al.* (1982). Schaefer (1981), in a study of Sky Patrol plates, found an optical transient of duration of less than 45 minutes which had occurred on 1928 November 17 inside the gamma-ray burst error box. It is not completely certain that the optical transient (1928) came from the gamma-ray burst source (1978), but because this seems very likely it has provided a focal point for our later observations. The position of the optical transient is consistent with that of the X-ray source (however, the error box of the X-ray source is substantially larger than that of the optical transient), but not with any of the radio sources.

Based on 4 m Cerro Tololo Inter-American Observatory (CTIO) B and V plates taken by M. Liller, Schaefer (1981) and Schaefer and Ricker (1982) have quoted a possible detection of a faint object ($B = 22.9 \pm 0.3$, $V = 21.5 \pm 0.4$) coincident with the optical transient. The same authors, using CCD exposures made with the 1.3 m McGraw-Hill telescope, were unable to confirm the existence of this object.

Infrared studies at 2.2 μm, also reported by Schaefer and Ricker (1983), did not reveal any object near the optical transient down to $m_K = 18.8$. Pedersen *et al.* (1982*b*) using CCD data obtained with the 1.5 m Danish telescope at the European Southern Observatory (ESO), La Silla, have reported the observation of two sources A and B, within the error box for the optical transient. Using further data from the same telescope, Pedersen and Motch (1982) have reported variability for the faintest of these, B. Subsequently, Schaefer, Bradt, and Seitzer (1982), using data from the 4 m CTIO telescope, reported variability of a source in the error region. This source is almost certainly our source A (Schaefer, Seitzer, and Bradt 1983).

II. OBSERVATIONS

We made a number of pictures in the period 1981 July 10 to 1982 December 14 at the ESO. A CCD camera attached to the 1.5 m Danish telescope was used for all observations. The camera employs an RCA 53612 chip with 312×520 pixels. The size of each pixel is 30 μm^2 corresponding to $0''.47$. The exposures were obtained through various filters, as listed in Table 1. Flat-field and interference fringe corrections were made using standard ESO routines.

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[1] Based on observations obtained at the European Southern Observatory.

TABLE 1

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Year	Date	Filter	Exposure Time (minutes)	Comments
1981	Jul 10	RG 665	20	
		V	20	
		B	20	
1981	Nov 26	Gunn *r*	30	
	Nov 27	Gunn *g*	30	a
	Nov 27	Gunn *r*	30	
	Nov 27	Gunn *g*	30	a
	Nov 28	Gunn *i*	2 × 30	
1982	Jul 3	RG 665	5 × 15	b
	Jul 4	RG 665	5 × 15	b
	Jul 6	RG 665	5 × 15	b
1982	Sep 17	*V*	2 × 20	a
	Sep 19	Gunn *r*	20	
	Sep 20	RG 665	3 × 45	
	Sep 21	RG 665	4 × 45	
1982	Oct 21	RG 665	5 × 45	
	Oct 22 (UT 4:51–7:13)	RG 665	3 × 45	c
	Oct 23 (UT 1:39–6:31)	RG 665	6 × 45	c
1982	Dec 13	RG 665	3 × 45	
	Dec 14	RG 665	3 × 45	

[a] Candidates A and B are not visible, and the exposures do not allow useful limits on magnitude.

[b] Some frames with poor seeing have been rejected.

[c] Observations were made simultaneously or nearly simultaneously with those of Schaefer, Bradt, and Seitzer 1982 who report a strong variability (*V* band) for a source which is almost certainly our source A (Schaefer, Seitzer, and Bradt 1983). Their observations were made on October 22 between UT 1:14h and 5:27h and on October 23 between UT 1:12h and 6:14h. Our observations (*R* band), integrated separately over the nights of October 22 and October 23, yield a difference $m_{R\ \mathrm{Oct\ 22}} - m_{R\ \mathrm{Oct\ 23}} = -0.7 \pm 0.6$.

During the 1981 November run, defocused standard stars were measured to allow the determination of color transformations between Johnson *V*, *R*, *I* and Gunn *g*, *r*, *i* (Thuan and Gunn 1976). The magnitude calibration was independently checked by comparison with the photometric data of Fishman, Duthie, and Dufour (1981). Measurements through the RG 665 filter correspond rather well to the Johnson *R* system. For a wide range of colors, the rms scatter was found to be ~ 0.1; estimates of the quoted errors in the magnitudes take this into account.

III. RESULTS OF OPTICAL OBSERVATIONS

The earliest CCD exposures of the gamma-ray burst region were obtained in 1981 July, before Schaefer's (1981) optical transient became known. The region of the transient was included in three exposures of 20 minutes each.

The combined information of all pictures taken in red light (RG 665 and Gunn *r* filter) in the time interval 1981 July 10 to 1982 July 6 is shown in Figure 1 (Plate L3). In addition to the error box of the optical transient, the figure indicates two radio sources, B and Q, the error circle of an X-ray source, and a quasar which was discovered during this work. Figure 2*a* (Plate L4) shows a close up of the region around the optical transient; Figure 2*b* (Plate L5) is identical except that the exposures were acquired in 1982 September to December.

a) *1928 Optical Transient Error Region*

Source A (see Figs. 2*a* and 2*b*) is the brightest of the two optical sources in the 1928 optical transient error box, and the one closest to the center. A previous statement that source A may be extended (Pedersen *et al.* 1982*b*) has not been confirmed by a numerical analysis of the image profile. Four average values of the *R*-magnitude of source A are given in Table 2. They are consistent with m_R being constant. The individual exposures have been examined for variability of source A. In no case have we observed statistically significant increases in brightness, but we cannot rule out occasional low states. Our color information on A, although meager, does indicate a red object. The average value of $m_R = 23.1$ is consistent with $m_v = 23.7 \pm 0.1$ of

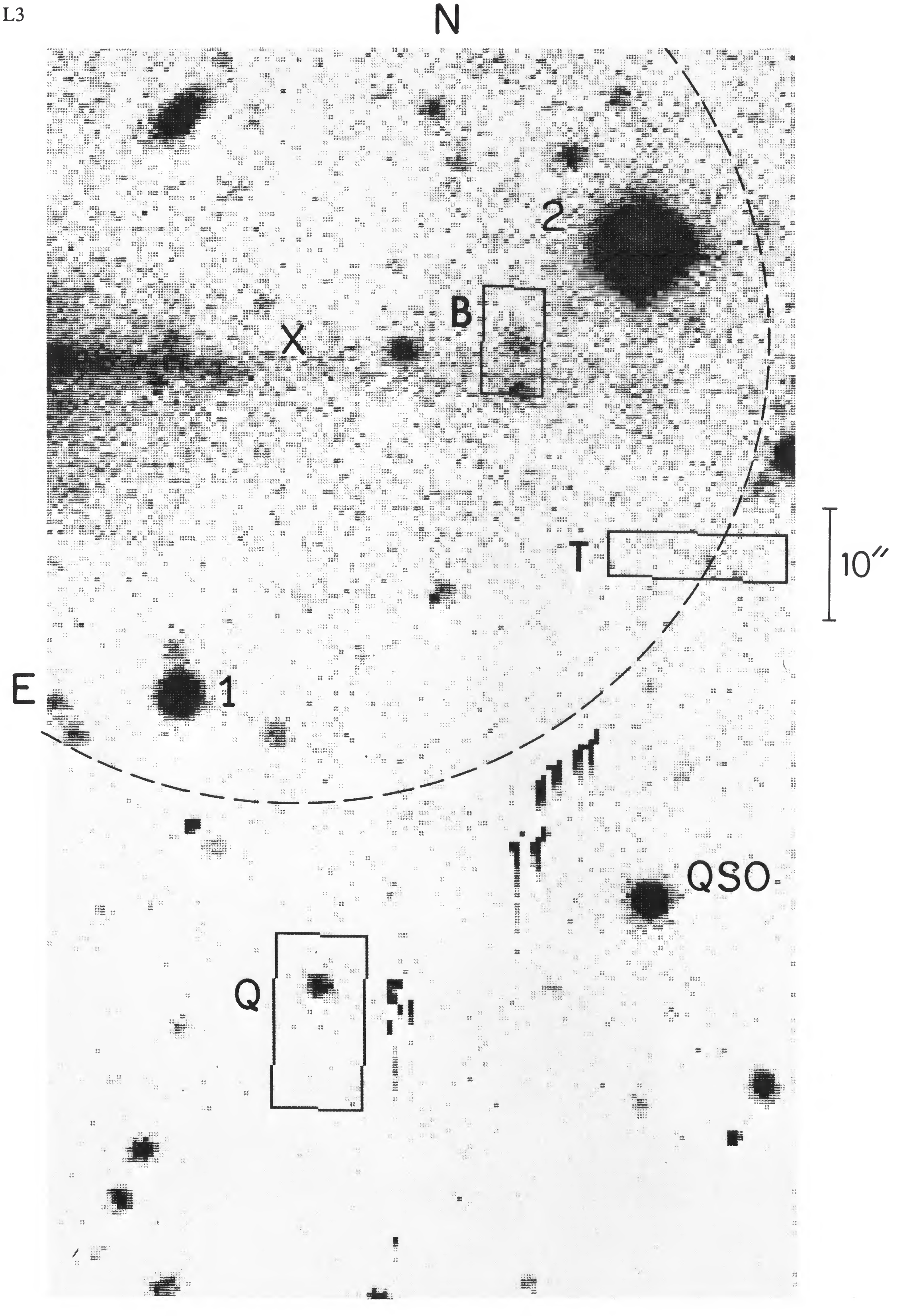

FIG. 1.—The sum of the RG 665 and Gunn *r* pictures from 1981 July to 1982 July. B and Q are the error regions of two radio sources reported by Hjellming and Ewald (1981) lying in the 1978 November gamma-ray burst error region. The radio source B should not be confused with our optical source B (Fig. 2). T is the error region of the 1928 optical transient reported by Schaefer (1981). The center of the error circle (with a 45″ radius, 90% confidence level) of the faint X-ray source (Pizzichini *et al.* 1981; Grindlay *et al.* 1982) is marked by ×. The QSO is marked, and so are the other two stellar-like objects (1 and 2) used in the position determinations of A and B (see text).

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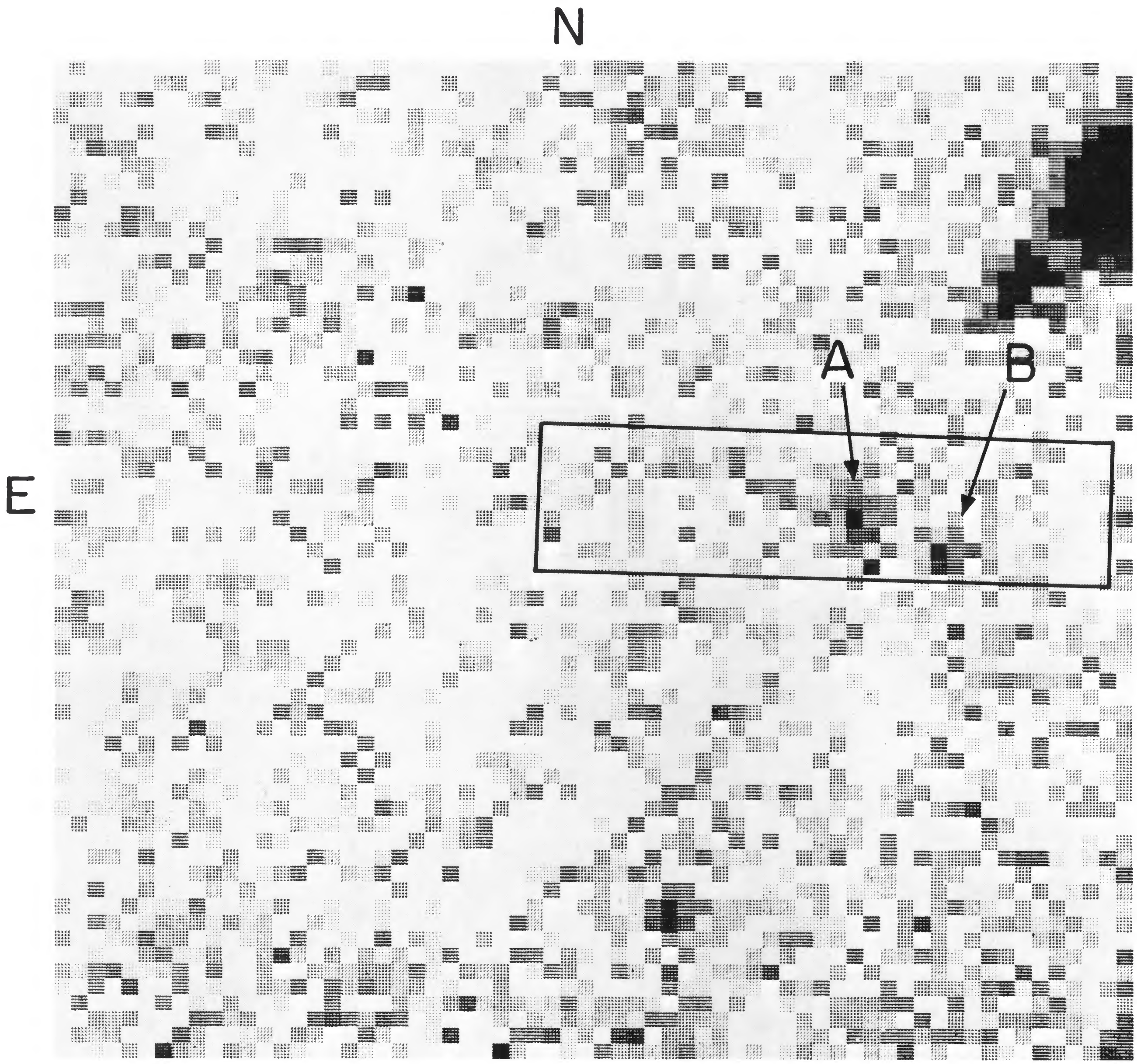

FIG. 2*a*.—Close-up of the sum of RG 665 and Gunn *r* pictures. A combined ~ 7.75 hr exposure taken between 1981 July and 1982 July. The two objects A and B are marked inside the 4″ × 16″ 1928 error region.

PEDERSEN *et al.* (*see* page L44)

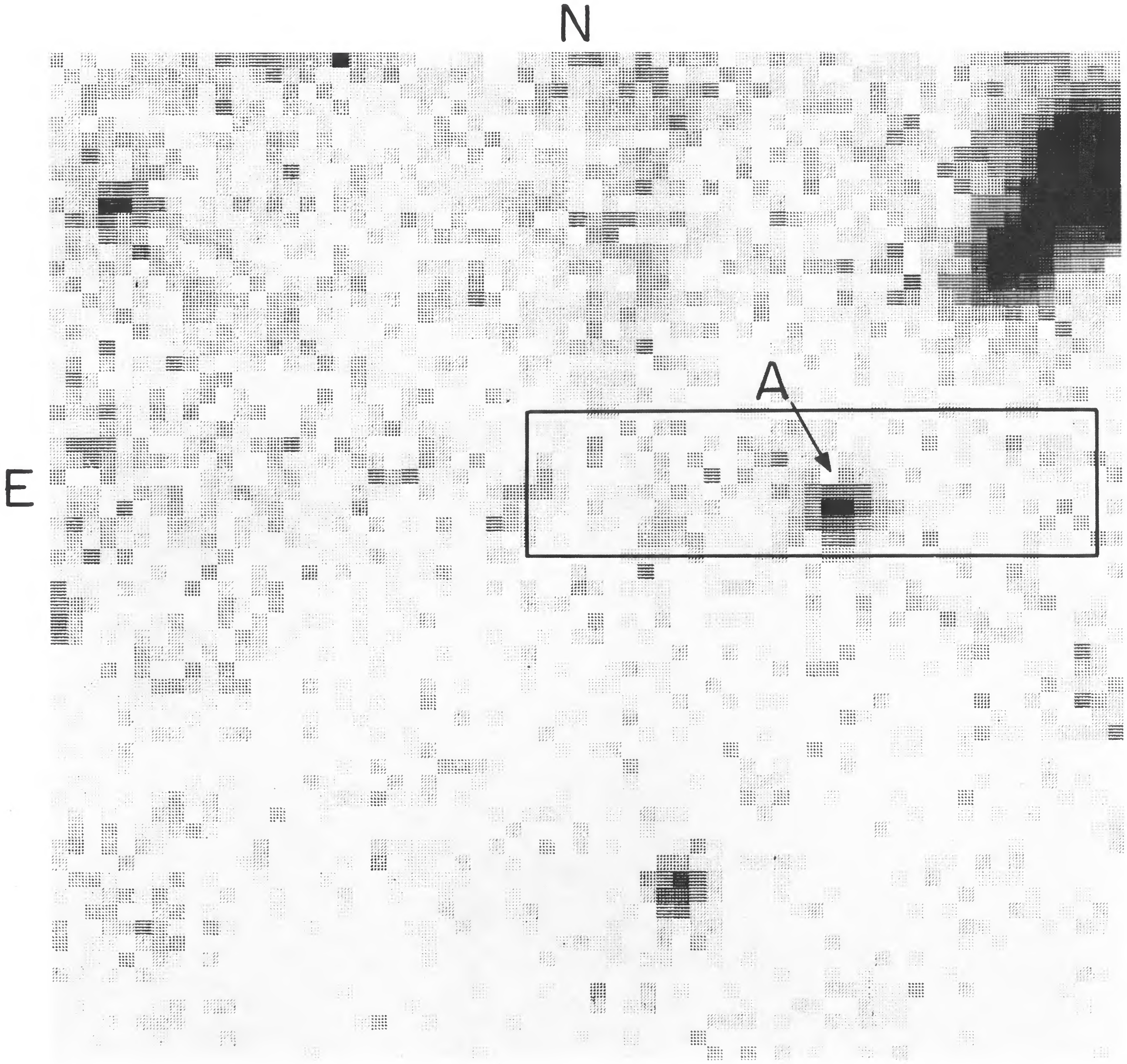

FIG. 2*b*.—Close-up of the sum of RG 665 and Gunn *r* pictures. A combined ~ 21.3 hr exposure taken between 1982 September and 1982 December. Source B is not visible anymore. An upper limit for the *R*-magnitude of source B is 25.0 (2 σ). Notice that this picture is deeper (~ 2.7 times more exposure) than the one in Fig. 2a.

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Schaefer, Seitzer, and Bradt (1983). We note that our observations made on October 22 and 23 were simultaneous or nearly simultaneous (see note *c* to Table 1) with those of Schaefer, Seitzer, and Bradt 1983 who report a strong variability (in the V band) of source A. They find source A brighter on October 22 than on October 23. Our observations (R band), integrated separately over the nights of October 22 and October 23, yield a difference $m_{R\,\mathrm{Oct}\,22} - m_{R\,\mathrm{Oct}\,23} = -0.7 \pm 0.6$.

Source B is apparent in two subsets (1981 November and 1982 July) of the data which were added in Figures 1 and 2*a*. It is not visible in any single exposure. The results of the photometry are given in Table 2. Color information is not available for this object. The significance of source B is $\sim 7\ \sigma$ when we combine the 6 brightest pixels nearest to the center of B; the image profile is consistent with that of a star. B is not seen in the later combined picture from 1982 September, October, and December (see Fig. 2*b*) which does go deeper than the 1981 July–1982 July sum picture (Fig. 2*a*).

An object was not observed at the position of a very faint photographic image which was seen on two CTIO 4 m plates taken by M. Liller (see Schaefer 1981). Since subsequent analysis indicates that the images may not be real (see Schaefer and Ricker 1983), we shall accept this.

The coordinates of A and B have been determined using transfer coordinates from the ESO QBS plates:

$$\mathrm{A}:\ \alpha(1950) = 01^{h}16^{m}25^{s}.74 \pm 0^{s}.05,$$

$$\delta(1950) = -28^{\circ}51'01''.6 \pm 0''.6;$$

$$\mathrm{B}:\ \alpha(1950) = 01^{h}16^{m}25^{s}.55 \pm 0^{s}.05,$$

$$\delta(1950) = -28^{\circ}51'02''.7 \pm 0''.6.$$

The relative position of A and B is determined to a higher accuracy, B is $2''.5 \pm 0''.3$ west and $1''.0 \pm 0''.3$ south of A. The above positions are the result of a linear interpolation method using the positions of three stellar-like objects marked in Figure 1. These three positions were determined by astrometry of an ESO Schmidt plate. They are:

$$1:\ \alpha(1950) = 1^{h}16^{m}29^{s}.209 \pm 0^{s}.02,$$

$$\delta(1950) = -28^{\circ}51'15''.38 \pm 0''.3;$$

$$2:\ \alpha(1950) = 1^{h}16^{m}26^{s}.260 \pm 0^{s}.02,$$

$$\delta(1950) = -28^{\circ}50'32''.51 \pm 0''.3;$$

$$\mathrm{QSO}:\ \alpha(1950) = 1^{h}16^{m}26^{s}.028 \pm 0^{s}.02,$$

$$\delta(1950) = -28^{\circ}51'32''.92 \pm 0''.3.$$

Since more than 50 years have elapsed since the optical transient, it is possible that the optical candidate is now many arc seconds from its position in 1928. We therefore made proper motion measurements using the 1981 November Gunn r and 1982 October data. No objects in the area common to these pictures have been found escaping in a statistically convincing way from an area within a 30″ radius from the error region of the 1928 optical transient. The upper limit on proper motion is magnitude dependent and practically limited to $0''.5$ per year for objects with $R = 22$.

b) *Quasar and X-Ray Source*

Pizzichini *et al.* (1981) reported a marginal detection of an X-ray source at a position consistent with the 1928 optical transient. The 90% confidence error circle (45″ radius) for this source (Grindlay *et al.* 1982) is shown in Figure 1. A stellar-like object ~ 60″ from the center of the X-ray error circle, labeled QSO in Figure 1, was the bluest object ($B - V = +0.1 \pm 0.3$) within a 5′ radius of the X-ray position. The position of the QSO is given above. We found from CCD exposures that $R = 19.64$, $V - R = 0.34$, and $R - I = 0.09$. Errors are difficult to estimate since they arise from the color transformation. A lower limit of 0.05 mag would apply to both magni-

TABLE 2

MAGNITUDES AND COLORS

SOURCE	MAGNITUDE	OBSERVATION DATE 1981 Jul–1982 Jul	 1982 Sep	 1982 Oct	 1982 Dec
A...........	R	23.16 ± 0.35[a]	23.19 ± 0.30[a]	22.96 ± 0.30[a]	22.94 ± 0.25[a]
	$R - I$	1.7 ± 0.9[a]	...	...	...
	$B - R$	1.4 ± 0.7[a]	...	...	...
	$B - V$	0.5 ± 1.0[a]	...	...	...
B...........	R	23.7 ± 0.6[a]	$> 25.0\ (2\ \sigma)$		$> 24.7\ (2\ \sigma)$

[a] Errors are 2 σ; they include counting statistics and estimated uncertainties resulting from the color transformations and from establishing the zero point.

tude and color. The upper limit to variability is ~ 0.15 mag.

A spectrum was obtained (390–680 nm) with the image-dissector-scanner on the Boller & Chivens spectrograph attached to the ESO 3.6 m telescope. The spectrum is probably that of a $z = 0.798$ quasar. The only certain feature is a broad emission line at 503 nm, which may be due to Mg II λ279.8 nm. The quasar is radio quiet; it does not appear on the 1465 and 4885 MHz VLA maps presented by Hjellming and Ewald (1981).

This quasar is a possible candidate for the source of X-rays even though it lies ~ 15″ outside the X-ray error circle. Therefore, the association of the X-ray source with the γ-ray burst source is uncertain.

IV. DISCUSSION AND CONCLUSIONS

The quiescent optical counterpart of the 1928 optical transient may still today lie inside the 1928 error region. If this is so, it could be our source A or B, but it is also possible that it is neither one, in which case $m_R > 25$ during our observations. Alternatively, in the ~ 54 years since the optical transient, the source may have moved out of the ~ 4″ × 16″ error region. For a distance of d pc and a transverse velocity of v km s^{-1}, the source would have moved in excess of 10″ if $v/d > 1$ km s^{-1} pc^{-1}. Thus for $d \sim 100$ pc, a tangential velocity in excess of ~ 100 km s^{-1} would be sufficient. Our proper motion search included all objects with $m_R \lesssim 22$ (this limit is due to photon statistics) inside a 1′.3 × 2′ area approximately centered on the 1928 error region (there is no stellar-like image brighter than $m_R \sim 22$ within 25″ of the 1928 error region). If the source has drifted out of the 1928 error region, it must either be fainter than this magnitude or it has drifted out of the field of our observations (i.e., a drift in excess of 1′).

The density of objects, both extended and stellar-like, in our data up to the limiting magnitude $m_R \approx 25$, is $\sim 5 \times 10^{-3}$ objects per arcsec^2. Of these, $\lesssim 50\%$ are stellar-like. Thus, there is a probability of ~ 3% of finding two objects to our limiting magnitude in the 4″ × 16″ error box. It seems therefore possible that the detection of two sources in the error box is accidental. This probability, considering only stellar-like objects, is ~ 0.8%. We cannot give an estimate of the probability of finding two such faint variable sources in the 1928 error region.

At first we selected our source B as a likely optical candidate for the gamma-ray burst source since B is variable and since no statistical evidence for variability of source A is present in our data. However, we now know that our source A is also variable (Schaefer, Seitzer, and Bradt 1983); thus, there is no longer a preference for B.

Possible mechanisms involving neutron stars have been proposed for the gamma-ray burst phenomenon. Among these we note: collisions with asteroids (Newman and Cox 1980; Van Buren 1981; Bonazzola *et al.* 1982), internal rotational energy release (Brecher 1982), and thermonuclear runaway (Woosley and Wallace 1982).

In what follows, we assume that a neutron star is responsible for the gamma-ray burst and that the optical counterpart of the 1978 November 19 gamma-ray burst is either our source A or B.

The approximate flux observed by us in the R band for the two candidate objects is between 1 and 2×10^{-15} ergs cm^{-2} s^{-1}. A bolometric correction cannot yet be applied for source B; however, for source A, $B - V \sim 1.2 \pm 0.3$ (Schaefer, Seitzer, and Bradt 1983). This leads to a bolometric flux of $1\text{–}2 \times 10^{-14}$ ergs cm^{-2} s^{-1}. Both our source B (this *Letter*) and our source A (Schaefer, Seitzer, and Bradt 1983) are variable.

We can address the question of the origin of the optical light in the nonbursting state, assuming blackbody emission. A single neutron star, a companion star, or an accretion disk around the neutron star could in principle be responsible for the optical emission. At maximum brightness, the sources A and B have an absolute magnitude $M_v \gtrsim +19$ for a source distance $\lesssim 100$ pc ($M_v \gtrsim +14$ for a distance $\lesssim 1$ kpc); interstellar absorption is negligible due to the high galactic latitude of the source. Thus, very low luminosity companion dwarfs are candidates (Sion 1979; Liebert 1979); binary evolution may produce very faint, low-mass companions (Ventura 1982). For an assumed source distance of 100 pc, any object with effective blackbody temperature T and typical dimension R_9 (in units of 10^9 cm) would qualify as long as $T^4 R_9^2 \approx 2 \times 10^{13}$ (a bolometric correction of a factor of 10 [see above] was applied here to our observed flux). As an example, for an accretion disk with $R_9 \approx 10$, T would be $\sim 7 \times 10^2$ K. For a single neutron star, with $R_9 \approx 10^{-3}$, $T \sim 7 \times 10^4$ K (100 pc distance). Therefore, it seems that a single neutron star can be excluded in the case of source A since its color information indicates a red object. The fact that the sources A and B are variable perhaps favors an accretion model with a disk and/or a companion star.

It can easily be shown that the observed optical light can be explained in terms of X-ray heating due to absorption of a persistent quiescent X-ray flux by a companion star and/or an accretion disk (see, e.g. equations and discussion in Pedersen *et al.* 1982*a*).

Let us assume that a thermonuclear flash is the origin of the gamma-ray burst (e.g., Woosley and Wallace 1982). Assuming that the observed X-ray flux comes from the gamma-ray burst source, and that it is due to accretion on a neutron star, we find that the time interval, t, between gamma-ray bursts is

$$t \sim 10^2 \frac{E_\gamma \varepsilon_x}{F_x \varepsilon_\gamma} \text{ s.} \qquad (3)$$

It is assumed here that ~ 100 MeV gravitational potential energy is released per accreted proton and that ~ 1 MeV thermonuclear energy is released per nucleon in the helium flash (Woosley and Wallace 1982). Here, E_γ is the observed gamma-ray burst fluence, F_x is the observed quiescent X-ray flux, ε_γ is the fraction of available nuclear energy that is emitted in gamma-rays, and ε_x is the fraction of available gravitational potential energy that is emitted in the X-ray energy band. With the observed value $E_\gamma \sim 3 \times 10^{-4}$ ergs cm^{-2} (Mazets *et al.* 1981), $F_x \sim 10^{-13}$ ergs cm^{-2} s^{-1} (0.5–3.0 keV band; Pizzichini *et al.* 1981; Grindlay *et al.* 1982) and $\varepsilon_\gamma \sim 0.25$ (Woosley and Wallace 1982), we find $t \sim 10^{12}$ ε_x s (thus, for $\varepsilon_x \sim 1$, t is about 30,000 years and about 4000 years if the flash were dominated by hydrogen). Since the interval between the 1978 November 19 burst to the previous burst from this source was not in excess of 50 years, it appears that F_x is variable and, on the average, much higher than observed or that most gravitational potential energy is not released in the 0.5–3.0 keV X-ray band (i.e., $\varepsilon_x \ll 1$), or that both of these possibilities occur (Schaefer 1981 came to similar conclusions). Alternatively, the thermonuclear flash model for γ-ray bursts is not correct.

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