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IDENTIFICATION OF THE VARIABLE X-RAY SOURCES GX 339−4 AND MXB 1659−29 BY THE SCANNING MODULATION COLLIMATOR ON *HEAO 1*

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ABSTRACT

Precise celestial positions have been obtained with the *HEAO 1* scanning modulation collimators for the highly variable X-ray source GX 339−4 (4U 1658−48) and the X-ray burst source MXB 1659−29. Both sources are identified with faint (17–18 mag) blue objects with He II λ4686 and λλ4640–50 emission.
Subject headings: X-rays: bursts — X-rays: sources

I. INTRODUCTION

The *HEAO 1* modulation collimator experiment is used to measure the positions of celestial X-ray sources to a precision of ∼10″ (Gursky *et al.* 1978; Schwartz *et al.* 1978). Precise positions are essential for identifying the optical counterparts of X-ray sources, especially those lying in the galactic plane. In this *Letter* we report the identification of the optical counterparts of two galactic X-ray sources, the highly variable source GX 339−4 and the burst source MXB 1659−29.

II. GX 339−4 (4U 1658−48)

a) Previous Work

The X-ray source GX 339−4 was discovered in 1973 during observations with the MIT detectors on *OSO 7* (Markert *et al.* 1973). These observations showed that the source was variable by a factor of at least 60 on time scales of hundreds of days. The source appeared to have two intensity states, a high state during which its intensity was ∼1/3 Crab, and a low state during which it was ≲5% Crab. The X-ray spectrum in the high state was very soft, with a $kT \approx 1.7$ keV and $N_H \approx 1 \times 10^{22}$ cm^{-2}. A spectral difference was observed between the high and low states which was consistent with either an increase in the absorption cutoff or an increase in temperature during the low state. There was no evidence in the *OSO 7* data for substantial variability on time scales from 3 minutes to 1 day.

Uhuru observations of the source confirmed the very soft spectrum (Jones 1977) during the high state. No evidence was found for short-term variability (<1 s) in the *Uhuru* data, although the source was observed only twice, and was near the limit of sensitivity to such variability (Forman, Jones, and Tananbaum 1976). There was evidence in the *Uhuru* data for variability of ∼75% on time scales of ∼0ᵈ1.

A possibly variable star was reported by Penston *et al.* (1975) in an optical study of the *Uhuru* error box. A difference in intensity of ∼0.5 mag was found on two Radcliffe plates. However, a group of six *B* and *V* plate pairs taken over a 12 day interval showed no evidence of variability (<0.2 mag) in the object. Neither colors nor spectra of the object were reported and it was not listed as a proposed identification.

HEAO 1 observations of GX 339−4 were carried out from 1977 September 10 to 14, while the source was in a low intensity state. Fluctuations in intensity of as much as a factor of 3 on time scales as short as 40 ms were observed with the NRL large area sky survey experiment (Samimi *et al.* 1978). These fluctuations appeared similar to episodes of variability seen in Cyg X-1 and Cir X-1. Variability on these time scales would not have been observed by *OSO 7* with its 3 minute time resolution. These fluctuations would have been missed by *Uhuru* if they were not a constant feature of the source, or if they are related to the overall intensity of the source. A recent *SAS 3* observation of the source during a high state also showed no evidence for variability on time scales from 1 to 500 s (Li, Clark, and Rappaport 1978; Li 1978, private communication).

b) Observations

A precise position for the source was determined from a superposition of 18 orbits of *HEAO 1* scanning modulation collimator data. The source was detected at the 25 σ level in both collimators at an intensity equivalent to 40 *Uhuru* counts. Only one of the multiple modulation collimator positions falls within the *Uhuru* and *Ariel 5* RMC positions for the source (Forman *et al.* 1978; Wilson *et al.* 1977; Eyles 1978). The error box center and corners are given in Table 1. A finding chart for the region is shown in Figure 1 (Plate L4), taken from the ESO quick blue survey.

The scanning modulation collimator data are ac-

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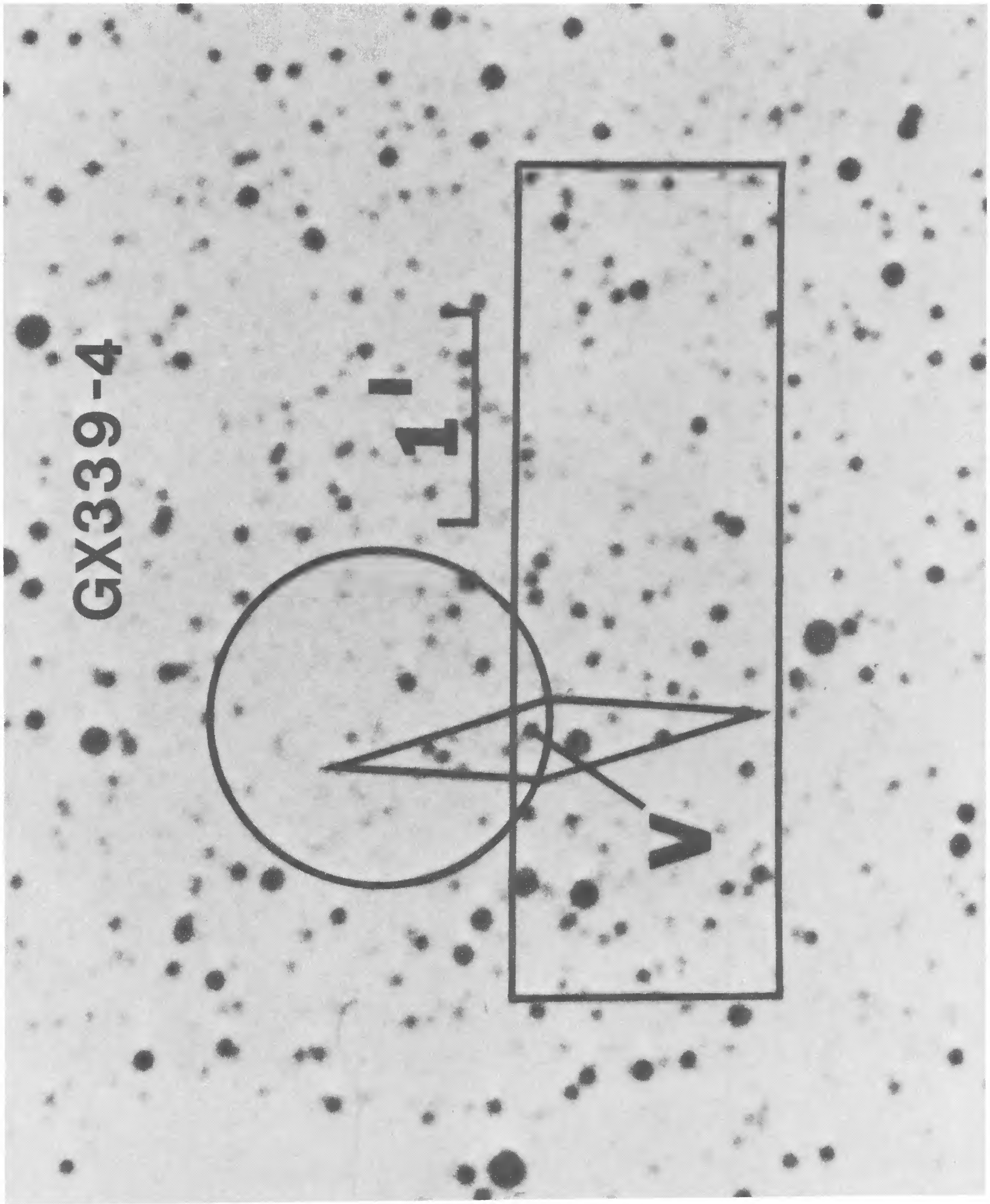

Fig. 1.—Finding chart for GX 339−4. The diamond indicates the *HEAO 1* MC error box for the X-ray source. The star marked *V* is identified as the optical counterpart. The circle and the rectangle indicate the *Ariel 5* and *Uhuru* error boxes, respectively.

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TABLE 1

HEAO 1 MC POSITIONS (1950)

	GX 339−4		MXB 1659−29	
	R.A.	Decl.	R.A.	Decl.
Center	$16^h59^m2\overset{s}{.}2$ 254.7592	−48°43′11″ −48.7197	$16^h58^m55\overset{s}{.}7$ 254.7321	−29°52′2″ −29.8672
90% confidence corners	10″ E, 62″ N 11″ E, 2″ N 10″ W, 62″ S 11″ W, 2″ S		8″ W, 62″ S 11″ W, 3″ S 8″ E, 62″ N 11″ E, 3″ N	
Star	$16^h59^m1\overset{s}{.}9$ 254.7579	−48°43′06″ −48.7183	$16^h58^m55\overset{s}{.}5$ 254.7313	−29°52′26″ −29.8739

cumulated in three energy channels (1.0–2.7, 2.7–5.4, and 5.4–13.3 keV). Fits of the rates in the three channels to thermal bremsstrahlung spectra yield values of $kT \approx 4$ keV and $N_H \approx 2 \times 10^{22}$ cm^{-2}. The hydrogen column density is consistent with that measured by *OSO 7* during the high state. The temperature, however, is clearly higher when the source is in its low intensity state. This apparent inverse correlation between intensity and spectral hardness is similar to that seen in both Cyg X-1 (Tananbaum *et al.* 1972) and Cir X-1 (Jones *et al.* 1974; Baity, Ulmer, and Peterson 1975).

Optical studies of objects in the *HEAO 1* MC error box were carried out (by J. E. G.) 1978 May 30–June 1 at Cerro Tololo Inter-American Observatory. Spectrophotometry was carried out using the SIT vidicon detector and spectrograph on the 4 m telescope. An emission-line object was discovered at the position of the star marked *V* in the error box (Fig. 1). The star is the one which had previously been observed as a possible variable by Penston *et al.* (1975). Photoelectric photometry of the object showed it to have a *V* magnitude of 16.6 ± 0.1, with $B - V = 0.84 \pm 0.1$ and $U - B = -0.24 \pm 0.1$. The 4 m spectra of the object revealed the presence of a broad Hα emission line and emission lines of He II λ4686 and C III/N III λλ4640–4650. The presence of emission lines characteristic of galactic X-ray sources (McClintock, Canizares, and Tarter 1975), the blue nature of the overall spectrum, and its location within the small X-ray error box make certain this object's identification as the X-ray source counterpart. Further optical studies of this object will be reported by Grindlay (1979).

c) *Discussion*

The general properties of the X-ray source GX 339−4 place it in the same class of X-ray emitters as Cyg X-1 and Cir X-1. The large intensity variations, with the inverse correlation between spectral hardness and intensity, are quite similar to Cyg X-1 and Cir X-1. The large, fast (<0.5 s) intensity fluctuations are also reminiscent of those of Cyg X-1 and Cir X-1. The primary difference appears to be that the fast fluctuations occur only when the source is in the low state, a correlation not observed in either Cyg X-1 (Oda *et al.* 1971; Rappaport, Doxsey, and Zaumen 1971) or Cir X-1 (Dower, Bradt, and Canizares 1979). There are a number of phenomena associated with one or both of the Cyg X-1 and Cir X-1 systems (e.g., binary period, shot noise, radio variability) which have not yet been reported in GX 339−4, but which should be sought with future observations.

Although the X-ray properties of the GX 339−4, Cyg X-1, and Cir X-1 systems exhibit similarities, it appears that the optical counterparts must be quite different. The optical counterpart of Cyg X-1, and possibly that of Cir X-1 (Whelan *et al.* 1977) as well, is a B0 supergiant. The color measures ($U - B$, $B - V$) of the GX 339−4 counterpart are, within errors, identical to those of the Cyg X-1 counterpart (Murdin and Webster 1971). If the GX 339−4 counterpart is a B0 supergiant, like the Cyg X-1 counterpart, then for the color measures to be identical the interstellar reddening ($E_{B-V} = 1.07$) and the absolute magnitude ($M_V = -5.8$) must be the same as for Cyg X-1. In that case, the measured visual magnitude implies that the distance to the source is 60 kpc, an unreasonable value. If, on the other hand, we assume that the X-ray luminosities are similar, then the distance to GX 339−4 is about twice that to Cyg X-1, or about 4 kpc. This distance, along with the average color excess ($B - V$) in the direction of GX 339−4 (~0.8 mag; FitzGerald 1968; Lucke 1978), imply that the counterpart has an absolute visual magnitude of ~1.0.

The X-ray to optical luminosity ratio (2–10 keV luminosity/3000–7000 Å luminosity) for the source (assuming $E_{B-V} = 0.8$) varies due to the X-ray variability from 15 to 150, larger than for Cyg X-1 (~0.1) or Cir X-1 (~5, but very uncertain). With a relatively high X-ray to optical luminosity ratio and the X-ray variability, it is not surprising that the optical counterpart was seen to have at least 0.5 mag variability. Indeed, if the system is a binary, as is likely, then barring an unfortunate inclination angle, light variations due to X-ray heating of the primary might be detectable. If the X-ray system contains a black hole, as is thought likely for Cyg X-1 and Cir X-1, then it may provide a better opportunity for optical studies of black hole/binary systems than Cyg X-1, where the intrinsic luminosity of the companion is high, or Cir X-1, which suffers from large interstellar extinction.

III. MXB 1659−29

a) *Previous Work*

The X-ray burst source MXB 1659−29 was discovered with *SAS 3* in 1976 October (Lewin, Hoffman, and Doty 1976). The burst intervals for this source were unusually stable, varying by ~1% over periods of 1 day (Lewin 1977). This source was also unusual in not having a detectable constant emission as well as bursts. The ratio of time-averaged steady luminosity to time-averaged burst luminosity was <25, and may possibly constrain thermonuclear flash models of X-ray burst sources (Lewin and Joss 1977) which predict higher values (>100).

Persistent emission from the source was first observed in 1978 independently by *SAS 3* (Lewin *et al.* 1978) and *HEAO 1* (Share *et al.* 1978). The *SAS 3* observation showed the intensity of the source to be varying by a factor of 4, with transitions between high (~8% of the Crab) and low states taking 40 s. No bursts were observed from the source by *SAS 3* during the 39 hour observation (Lewin 1978). A preliminary position for the source was determined from two quick-look orbits of scanning modulation collimator data (Griffiths *et al.* 1978*b*).

b) *Observations*

A refined position for MXB 1659−29 has been obtained from a superposition of 20 orbits of production data from the *HEAO 1* scanning modulation collimator experiment. The detection significance is 20 σ in each collimator. The refined error box is substantially smaller than the one derived from quick-look data and lies slightly south of it. The center and error box corners are given in Table 1. A finding chart for the region is given in Figure 2 (Plate L5).

Optical studies of the *HEAO 1* MC error box were carried out (by J. E. G.) at the Cerro Tololo Inter-American Observatory 1978 May 30 to June 1. Deep 4 m plates of the field were taken in the U and B bands to search for a UV excess optical candidate. Such an object was discovered within the error box on the CTIO plates (see Fig. 2); it was also independently pointed out by W. Liller (private communication in Griffiths *et al.* 1978*a*) as being relatively blue on the Palomar Sky Survey plates. Photoelectric photometry on June 1 showed that the object has a V magnitude of 18.3, with $B - V = 0.37$ and $U - B = -0.38$. Although the photometry is complicated by two nearby stars, we estimate uncertainties of ± 0.2 mag in V and ± 0.15 mag in the color measures. Spectrophotometry (4000–7000 Å) revealed a flat continuum and a suggestion of evidence for the presence of He II λ4686 and C III/N III λλ4640–4650 emission lines. Further details of the optical data reported here are given by Grindlay (1979), and higher-resolution spectrophotometry in which the λλ4640–4650 and λ4686 emission are clearly visible will be reported by Canizares, McClintock, and Grindlay (1979). Once again, the presence of characteristic emission lines, an overall blue spectrum, and location within a very small X-ray error box make certain the identification of this object as the optical counterpart.

c) *Discussion*

The discovery of persistent emission from MXB 1659−29 in the present observation removes the primary observational fact distinguishing it from other X-ray burst sources. It is possible that the source is the same as 4U 1704−30, as it lies only 0°.1 outside the *Uhuru* error box. While it is clear that during times of burst activity the steady to burst luminosity ratio is low (and thus still of special interest for burster models), it is possible that the long-term ratio is compatible with that of other burst sources. The optical counterpart for MXB 1659−29 is very similar to the counterparts for the burst sources MXB 1636−53 and MXB 1735−44 (McClintock *et al.* 1977), as well as to the counterparts for many other X-ray sources where the X-ray to optical luminosity ratio is greater than 100.

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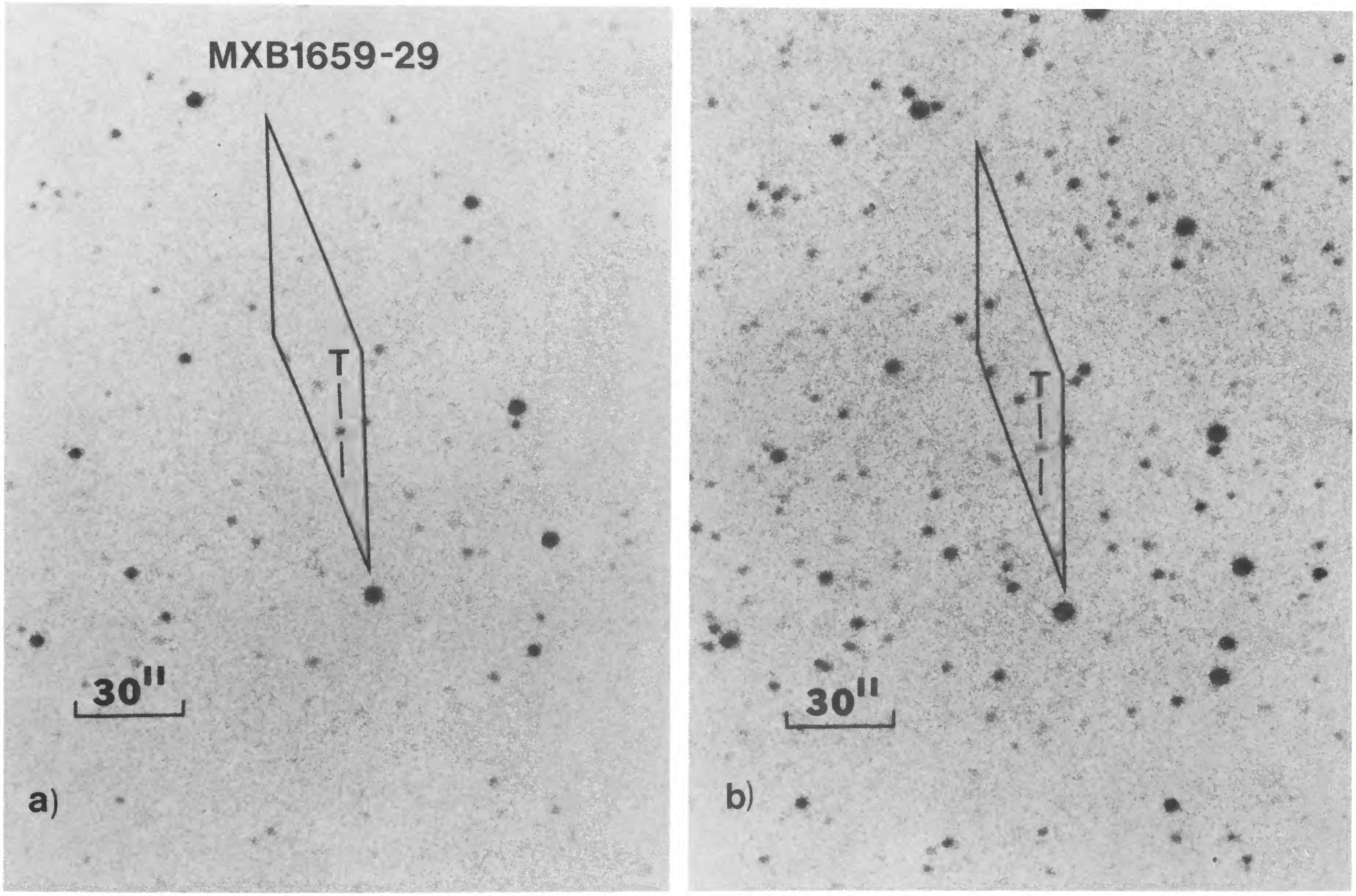

FIG. 2.—Finding chart for MXB 1659−29. The star marked *T* is identified as the optical counterpart. The ultraviolet excess of the optical counterpart is shown in a comparison of the *U* band (*a*) and *B* band (*b*) 4 m plates. The *HEAO 1* MC error box for the source is indicated by the diamond.

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