THE ASTROPHYSICAL JOURNAL, 203:448–454, 1976 January 15

A SEARCH FOR OPTICAL COUNTERPARTS OF NINE GALACTIC X-RAY SOURCES

ARTHUR DAVIDSEN, ROGER MALINA, AND STUART BOWYER
Astronomy Department and Space Sciences Laboratory, University of California, Berkeley
Received 1975 May 21; revised 1975 June 23

ABSTRACT

Results of a photographic and spectrophotometric search to $B \sim 18.5$ for the optical counterparts of nine galactic X-ray sources with good positions are reported. The sources included in this survey are 3U 1709−23, 1728−16, 1728−24, 1758−20, 1758−25, 1811−17, 1813−14, 1837+04, and 1908+00. Optical candidates for six of these sources are discussed, including blue objects which may be the optical counterparts of 1709−23 and 1728−16, a distant B star near 1908+00, and a very unusual strong emission line object which is probably associated with 1728−24 (GX 2+5). Coordinates, magnitudes, colors, spectral data, and finding charts are presented.

Subject heading: X-ray sources

I. INTRODUCTION

There are now at least eight optically identified X-ray sources in the Galaxy (omitting supernova remnants), plus one which has an infrared counterpart but where interstellar extinction is too large to allow visible light observations (Cyg X-3) and one which is in another galaxy (SMC X-1). Of the eight which are most firmly identified, five (Cyg X-1, Her X-1, Cen X-3, 3U 0900−40, 3U 1700−37) are definitely established as binaries where mass transfer onto a compact star is the mechanism which generates X-rays, while the nature of the remaining three (Sco X-1, Cyg X-2, and 3U 0614+09) remains in doubt.

Further optical identifications are needed to extend our knowledge of the nature and distribution of compact X-ray sources. In particular, although the X-ray sources are concentrated in the general direction of the galactic center, none of this group (except Sco X-1) have yet been identified. Published search efforts (e.g., Kunkel *et al.* 1970; Murdin *et al.* 1974; Jones *et al.* 1974) have been limited to photometry of the brightest stars, and even these surveys are not at all complete. Nevertheless, it has been generally assumed that these sources are in fact near the galactic center (except Sco X-1 at high galactic latitude, with $d = 250$–500 pc, Felten and Humpreys 1973). Based on this assumption, X-ray luminosity functions have been derived (Margon and Ostriker 1973), and discussions of the stellar population with which these sources are associated have been frequent. Only through further optical identifications will these important questions be clarified. In addition to the unanswered questions about the collective properties of compact X-ray sources, there remains the problem of understanding the nature of individual objects of the Sco X-1 class. Despite intensive study of Sco X-1 itself and several reports of possible periods suggesting a binary system (Gottlieb *et al.* 1975; Crampton and Cowley 1975), no real understanding of its nature has emerged. The recently suggested identification of 3U 0614+09 (Murdin *et al.* 1974; Davidsen *et al.* 1974) provides encouragement that there are other similar sources, and the study of several members of this class may now hold the greatest promise of further progress.

II. SEARCH CRITERIA

In this paper we discuss our efforts to identify optical counterparts of the nine galactic X-ray sources listed in Table 1. These comprise all but one of the unidentified sources listed in the 3U catalog (Giacconi *et al.* 1974) with error boxes less than 30 arcmin² and which are north of $\delta = -26°$ (3U 0115+63 is not included). They all lie in the galactic longitude range $0 < l < 40°$ and have $|b| < 10°$, with a mean galactic latitude $\langle |b| \rangle = 3.9°$, and all of them are variable. Several of the sources also have positions determined with the University College London X-ray telescope aboard Copernicus (Willmore *et al.* 1974), and these are comparable to or more accurate than those in the 3U catalog. For three of them weak radio sources have been found which may be associated with the X-ray objects. In Figures 1–3 (Plates 11–13) we present finding charts for all of the sources in Table 1 which have not previously been published.

Two major obstacles to success in finding optical counterparts of galactic X-ray sources are (1) the large size of most of the X-ray error boxes and (2) possibly severe interstellar extinction for distant sources in the galactic plane. Although our sample is limited to only those sources with the best determined positions, each error box still contains a rather large number of stars. Since it would be impractical to make a detailed study of each star in these fields, some criteria must be applied to select for further study a small number of stars which have a higher than average probability of being associated with the X-ray source. Where no other information is available to single out a particular candidate, the criteria we have chosen are to search for stars which are relatively bright in the ultraviolet, and variable stars.

TABLE 1

SEARCH LIST OF UNIDENTIFIED GALACTIC X-RAY SOURCES

3U	Other Name	Maximum X-ray Flux 2–10 keV (10^{-10} ergs cm^{-2} s^{-1})	Max/ Min	l, b	Size of Smallest X-ray Error Box (square arcmin)	Ref.	Associated Radio Source	Estimated Interstellar Extinction	Optical Candidate
1709−23...	Oph X-2	6.6	5	0.5, +9.2	27	(1)	No	Low	Yes
1728−16...	GX 9+9	44	1.7	8.5, +9.0	1.3	(2)	No	Low	Yes
1728−24...	GX 2+5, GX 1+4	10	2–4*	1.9, +4.8	0.5	(3)	No	High	Yes
1758−20...	GX 9+1	100	2	9.1, +1.2	0.8	(2)	Yes (a)	High	No
1758−25...	GX 5−1	190	2	5.0, −1.0	0.05	(4)	Yes (b)	High	Yes
1811−17...	GX 13+1	65	3	13.5, +0.1	1.8	(1)	No	High	No
1813−14...	GX 17+2	100	1.5	16.4, +1.3	3.2	(1)	Yes (c)	High	Yes
1837+04...	Ser X-1	46	2	36.1, +4.9	4.3	(1)	No	Moderate	No
1908+00...	Aql X-1	34	3	35.7, −4.0	7.2	(1)	No	Moderate	Yes

* Variability from observations above 15 keV (Lewin *et al.* 1971).

REFERENCES.—X-ray error boxes: (1) Giacconi *et al.* 1974; (2) Willmore *et al.* 1974; (3) Mason 1974; (4) Davison 1973. Radio sources: (*a*) Zaumen *et al.* 1972; (*b*) Braes *et al.* 1972; (*c*) Hjellming and Wade 1971*b*.

Photographic searches for objects with an ultraviolet excess led to the first optical identifications of compact galactic X-ray sources, Sco X-1 (Sandage *et al.* 1966) and Cyg X-2 (Giacconi *et al.* 1967). This ultraviolet excess was expected on the hypothesis that the X-ray bremsstrahlung spectrum could be extrapolated into the optical band. While this hypothesis has not been supported by more recent work, it has nevertheless turned out that all optically identified galactic X-ray sources do have an ultraviolet excess. For some of these (e.g., Cyg X-1) this is because the X-ray sources are associated with bright early-type supergiants, while for others (e.g., Her X-1) it is due to the strong heating of a fairly cool stellar atmosphere by an X-ray emitting binary companion. The latter may also be the correct explanation for Sco X-1 and Cyg X-2, but for these sources the situation is not yet clear.

Our second selection criterion, optical variability, also seems well supported. The optical counterparts of the identified X-ray sources are all variable, although for those associated with luminous early-type stars the amplitude of the variation is quite small. For the lower optical luminosity sources like HZ Her and Sco X-1, however, the optical variability exceeds 1 mag. Such sources can easily be discovered photographically to very faint limits.

The second important limitation in an optical search for X-ray sources is provided by interstellar extinction, which may be very large for some of the sources considered here if they are typically at distances ~10 kpc. However, several of the sources in Table 1 are at moderately large distances from the galactic plane. If they lie outside the very narrow layer of interstellar dust, they may suffer only a small amount of extinction in spite of their great distance. A qualitative impression of the magnitude of extinction in each of the fields may be obtained from comparison of the blue and red plates of the Palomar Sky Survey. In addition, the extinction given in the galactic survey by Neckel (1967) for stars within several degrees of the X-ray positions yields information which is relevant for those fields where the reddening is not patchy. Our impression of the extinction for each of the X-ray fields is given in Table 1.

After a small number of candidates have been found by applying the criteria discussed above, spectroscopic observations may be undertaken to determine whether these candidates display any unusual features which might suggest an association with an X-ray source. Of particular interest are emission lines of N III λ4640 and He II λ4686, which are present in almost all of the previously identified X-ray sources (McClintock *et al.* 1975), but other peculiarities may also be suggestive.

III. SELECTION OF OPTICAL CANDIDATES

For three of the sources in Table 1 (1728−24, 1758−25, and 1813−14) strong optical candidates have previously been suggested on the basis of good positions and other information. Coordinates and other data for these candidates, discussed in detail below, are given in Table 2.

We have searched the fields of the remaining six sources in Table 1 for objects with an ultraviolet excess. Pairs of plates on Kodak 103aO emulsion with ultraviolet (UG-2) and blue (GG-13) filters were obtained with the 91-cm Crossley reflector of Lick Observatory and with the 76-cm telescope of Leuschner Observatory in 1974 May and June. The limiting magnitudes of our search are typically $U \approx 18$, $B \approx 18.5$. Several blue plates were also obtained to search for variability with a typical limit of 0.2 mag plate to plate for the faintest stars. For X-ray sources which are associated with early-type supergiants (e.g., Cyg X-1) these limits allow a complete search to distances beyond the galactic center as long as the reddening is low or moderate [$E(B - V) \lesssim 2$ mag]. This is also true for sources like Cyg X-3 which are not associated with supergiants but which nevertheless may have extremely high optical luminosity (Davidsen and Ostriker 1974). For sources with intrinsically low optical luminosities, such as Cyg X-2 with $M_v \approx +5$ (Kraft and Demoulin 1967; Cathey and Hayes 1968),

TABLE 2

OPTICAL CANDIDATES

3U	α (1950.0)	δ (1950.0)	$V_{scanner}$	$(B - V)_{scanner}$	Spectrum
1709−23.....	17h09m12s.1	−23°20′22″	18.2	−0.1	Blue continuum, Balmer absorption lines, ultraviolet excess
1728−16.....	17 28 50.1	−16 55 35	16.6	0.0	Blue continuum, no strong features, ultraviolet excess
1728−24.....	17 28 57.8	−24 42 45	18.7	...	Strong Hα emission; Hβ, He I 5876 emission highly reddened; probable [Fe VII] and [Fe X] emission
1758−25.....	17 58 03.7	−25 04 40	17.7	1.3	Hα, Hβ absorption; highly reddened early type
1813−14.....	18 13 10.9	−14 03 15	17.5	1.2	G, apparently normal
1908+00.....	19 08 39.3	+ 0 29 01	16.0	0.57	B5 V, moderately reddened, normal

NOTE.—Coordinates are expected to be accurate to ±5″. Magnitudes and colors have errors of ~±0.1 mag.

our search will extend as far as ~5 kpc only for those fields where the reddening is low.

Iris photometry of a large number of stars (up to 100) both inside and surrounding the X-ray error boxes was done with the Cuffey variable iris photometer of the Berkeley Astronomy Department, and objects which were relatively bright in U compared with B were noted. This technique has previously revealed optical candidates for Her X-1 (Davidsen *et al.* 1972) and 3U 0614+09 (Davidsen *et al.* 1974). In this manner ultraviolet-bright candidates were found near the X-ray positions for 3U 1709−23, 3U 1728−16, and 3U 1908+00. Data for these objects are also listed in Table 2.

All of the optical candidates in Table 2 have been observed spectrophotometrically with the image-tube scanner (ITS) at the 3-m telescope of Lick Observatory in 1974 July. Our spectroscopic data suggest that several of these candidates are peculiar objects which may indeed be X-ray counterparts, while others are apparently normal stars. Each of the sources in our survey is discussed in the next section.

IV. OBSERVATIONS OF INDIVIDUAL SOURCES

a) 3U 1709−23

The only positional information available for this source is the 3U catalog, where its error box is the largest of any of the sources studied in this paper. With a maximum X-ray flux of 6.6×10^{-10} ergs cm^{-2} s^{-1} it is also the weakest of the sources under consideration. The error box is shown in Figure 1.

This field has been studied previously by Bahcall and Bahcall (1975), who noted as an interesting candidate an object which appears very blue on the Palomar Sky Survey. This candidate, which lies just outside the 3U error box, is marked on the finding chart in Figure 1, and its coordinates are given in Table 2. Comparison of blue and ultraviolet plates obtained with the Crossley reflector show that this object, alone among the 54 stars examined, had a marked ultraviolet excess. Spectrophotometry with the ITS reveals a flat continuum with Balmer absorption lines and yields $V = 18.2$, $B - V = -0.1$. The signal-to-noise ratio achieved so far does not allow the reality of any other features to be established, but there is a suggestion of emission which might be He II 4686. In addition there are several apparent absorption features which are present in one spectrum but not present in another. Further spectroscopic observations are required to establish the reality of these suggested features. No variability has been detected on five blue plates.

b) 3U 1728−16

Small error boxes for this source have been obtained with *Uhuru* (Giacconi *et al.* 1974) and with *Copernicus* (Willmore *et al.* 1974), but the two determinations do not overlap (see Fig. 1). The only previous optical work reported for this field is that of Murdin *et al.* (1974), who give photoelectric U, B, and V magnitudes for six stars without identifying a good candidate.

In spite of the uncertainty of the X-ray position, this source provides a good opportunity for an optical identification because the reddening in this region appears to be quite low and uniform. An estimate of the reddening can be obtained from examination of HD 158661, a B0.5 Ib star only ~12′ from the X-ray source position. This star gives $E(B - V) = 0.35$ at a distance of 4.4 kpc (Neckel 1967). Because this field is at relatively high galactic latitude ($b = +9°$), the line of sight has left the dust layer at this distance and the reddening should not be appreciably larger even for much more distant objects. This conclusion is supported by studies of the nearby globular cluster NGC 6356 ($l = 6°$, $b = +10°$) and its surrounding field (Sandage and Wallerstein 1960; Wallerstein 1962) which give $E(B - V) = 0.5$ at 10 kpc. Thus, if the optical counterpart of 3U 1728−16 is similar to any of the previously identified X-ray sources, it should have an obvious ultraviolet excess, even if it is as distant as the galactic center.

Comparison of ultraviolet and blue plates obtained with the Crossley reflector reveals an object with a marked ultraviolet excess less than 30″ from the optimum *Copernicus* position for 3U 1728−16. This candidate is shown in Figure 1, and its coordinates are given in Table 2. Although the object lies just outside both the *Copernicus* and *Uhuru* error boxes, it must be

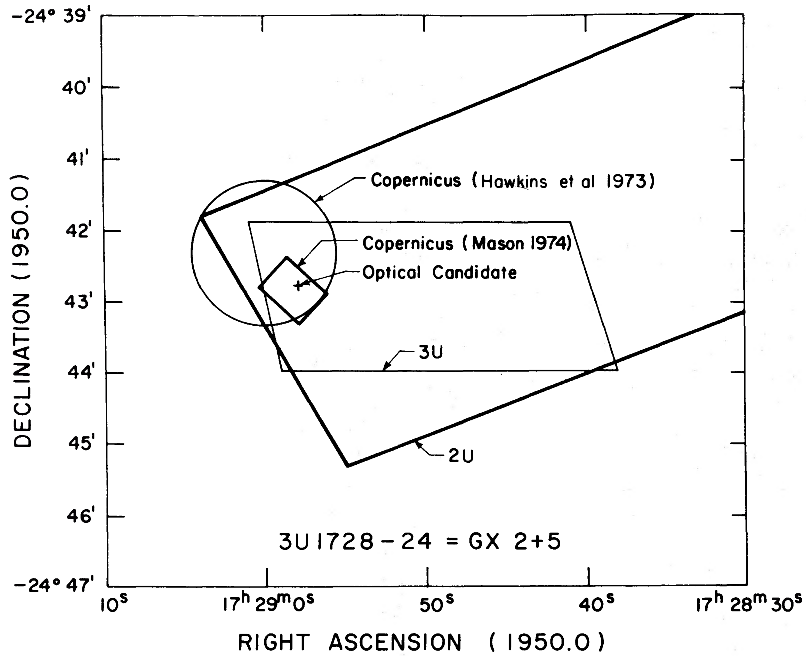


FIG. 4.—Error boxes for 3U 1728−24 = GX 2+5 (90% confidence). The position of the optical candidate discussed in the text is also indicated.

considered a good candidate in view of the disagreement between the X-ray positions. Iris photometry compared with the photoelectric magnitudes of other stars in the field given by Murdin *et al.* (1974) yields $B = 16.4$, $U - B = -0.5$ for this object.

Spectrophotometry of the candidate with the ITS reveals a flat continuum with no strong features and $V = 16.6$, $B - V \approx 0.0$. The difference in the magnitudes obtained with the ITS and from photographic photometry is within the errors of the separate results (± 0.1 mag). On one spectrum Hβ appears to be present very weakly in absorption, but on a second spectrum there is, if anything, emission at this wavelength. However, neither spectrum is of sufficient quality to be entirely convincing. The limit on variability for five plates is ± 0.2 mag.

c) 3U 1728−24

All of the error boxes which have been reported for this source are illustrated in Figure 4. The formal confidence of each of these is 90 percent, except for the one due to Hawkins *et al.* (1973), where it is unstated. Since the most recent and smallest error box derived from *Copernicus* observations (Mason 1974) is consistent with all the earlier, larger boxes, we feel justified in placing considerable confidence in it. According to Mason, the optimum position is $\alpha = 17^{h}28^{m}58^{s}.3$, $\delta = -24°42'50''$ (1950.0).

In a search of the region around the position due to Hawkins *et al.* (1973), Glass and Feast (1973) have found a bright infrared object which they identify with the star marked in Figure 2. This star is only $\sim 9''$ from the current optimum *Copernicus* position for 3U 1728−24, which strengthens the possible association.

We have done spectrophotometry of this candidate with the ITS on 1974 July 14, the results of which are summarized in Table 2. Almost all the visible emission of this object is contained in the Hα emission line, but a faint continuum and emission at Hβ and He I λ5876 are also definitely present. The ratio of Hα to Hβ indicates $A_v \approx 10$ assuming an intrinsic ratio appropriate to radiative recombination in case B (Brocklehurst 1971). There may also be weak emission of [O III] $\lambda\lambda$4959, 5007, as reported by Glass and Feast, but further observations are required to verify their presence. We have also observed several other probable emission features, the strongest of which may be identified with [Fe VII] λ6086 and [Fe X] λ6374. These lines are often strong in the spectra of novae well after maximum (Joy and Swings 1945; Ciatti and Rosino 1974), and also appear in some symbiotic stars (Webster and Allen 1975) and in the Seyfert galaxy NGC 4151 (Seyfert 1943; Oke and Sargent 1968).

A more extensive discussion of this object is presented elsewhere (Davidsen *et al.* 1976), where it is suggested that the emission-line spectrum arises in a compact nebula surrounding a central X-ray source. According to Glass and Feast (1973) the infrared observations indicate the presence of a luminous late-type star. A compact object in orbit about this star may then produce the observed X-rays by accretion, as in standard models (e.g., Davidson and Ostriker 1973). Photoionization of the surrounding nebula, perhaps the remnant of a previous nova-like outburst, leads to the observed emission line spectrum, including the high ionization states of Fe, which require a hard spectrum extending up to X-ray energies in this model.

In view of the excellent positional agreement of the candidate and the X-ray source, as well as the plausible relationship of the unusual optical spectrum to the X-ray emission, we consider that this object is very probably associated with 3U 1728−24. Since the X-ray source is variable on time scales as short as 2 minutes (Lewin *et al.* 1971), it may be possible to establish this identification even more firmly by observation of correlated X-ray and optical variability.

d) *3U 1758−20 = GX 9+1*

The 3U error box for this source is quite small, and there is also a very small *Copernicus* error box (Willmore *et al.* 1974) which overlaps it. Both of these are shown in Murdin *et al.* (1974). An earlier X-ray position which includes both of these was reported by the MIT group (Schnopper *et al.* 1970) and is shown in Kunkel *et al.* (1970). A weak variable radio source was found (Zaumen *et al.* 1972) within the MIT error box, but its position is not in agreement with the smaller 3U and *Copernicus* error boxes, so its relationship to the X-ray source is in doubt. Willmore *et al.* (1974) discount the discrepancy in position by noting that Sco X-1 has associated radio emission in lobes which are about 1′ away from the X-ray source. However, the variable component of the Sco X-1 radio source is coincident with the X-ray and optical emission (Hjellming and Wade 1971*a*), so the discrepancy in the case of 3U 1758−20 should not be overlooked. No optical objects are visible at the radio position to the limit of the Palomar Sky Survey prints.

All but three of the stars in the *Copernicus* and 3U error boxes are below our plate limit ($U \sim 17.8$) for this field, which is heavily reddened. No ultraviolet-bright candidates were found.

e) *3U 1758−25 = GX 5−1*

The most accurate position for this source is based on three lunar occultation observations from *Copernicus* (Davison 1973). A weak radio source which may be associated with the X-ray source has also been detected (Braes *et al.* 1972). The radio and X-ray positions are consistent at the 95 percent confidence level (see Davison 1973 for a finding chart). The larger error boxes obtained by *Uhuru* (Giacconi *et al.* 1974) and *Copernicus* (Willmore *et al.* 1974) are also consistent with the lunar occultation position (see Murdin *et al.* 1974 for a finding chart which includes these).

Within the very small error box (an ellipse with dimensions 35″ × 7″) derived by Davison (1973) there is only one star visible on the Palomar Sky Survey prints. This star, designated number 22 in Davison (1973), is therefore a candidate for the optical counterpart of GX 5−1. Its coordinates are given in Table 2.

We have observed star 22 with the ITS and find $V = 17.7$; the continuum is quite red, corresponding to $B - V \approx 1.3$. Hα and Hβ appear to be present in absorption, as do the sodium D lines. No other features are very convincing, and it thus appears likely that star 22 is a reddened early-type star. No emission lines are detected. Additional observations of this candidate must be obtained before any firm conclusion can be drawn about its possible association with GX 5−1.

f) *3U 1811−17*

This source has a very small *Uhuru* error box, shown in Figure 2. About 1′ NE of the X-ray position is the 10th magnitude B8 star HD 167168. Blue and ultraviolet Crossley plates have revealed no stars with an ultraviolet excess and no variables among the 35 stars measured.

g) *3U 1813−14 = GX 17+2*

An accurate position for this source was first obtained by the MIT group (Schnopper *et al.* 1970), and an unsuccessful search of the field for peculiar optical objects to $B \approx 17$ has been reported by Kunkel *et al.* (1970). Subsequent observations with *Uhuru* lead to a position which is consistent with the MIT result (Tananbaum *et al.* 1971). A rapidly variable radio source was discovered very near the center of the MIT error circle and also within the *Uhuru* error box by Hjellming and Wade (1971*b*), who remarked that the behavior of this source is similar to that of the variable radio source associated with Sco X-1. Tananbaum *et al.* (1971) have discussed the similarity of the X-ray spectra and time variability of GX 17+2 and Sco X-1. The ratios of X-ray fluxes and radio fluxes both suggest a distance for GX 17+2 of about 4 times that of Sco X-1, or 1–2 kpc (cf. Felten and Humphreys 1973 for the Sco X-1 distance), assuming they are intrinsically similar objects. The major difference between the two sources is that GX 17+2 displays a low-energy X-ray cutoff suggesting attenuation by $\sim 2 \times 10^{22}$ atoms cm^{-2} (Tananbaum *et al.* 1971). If this is due to interstellar matter, a much greater distance is suggested for GX 17+2; if it is due to circumstellar matter, it is likely that the intrinsic optical properties of these objects may be quite different.

Within the very small error box of the GX 17+2 radio source there is only one optical object visible on the Palomar Sky Survey prints. This object has previously been noted as a candidate for the optical counterpart of GX 17+2 by Tarenghi and Reina (1972). Spectrophotometry with the ITS reveals that this star has an apparently normal G-type spectrum. We find $V = 17.5$, and the color corresponds to $B - V \approx 1.2$. There is no reason at present (beyond the positional coincidence) to believe that this star is related to GX 17+2.

h) *3U 1837+04*

The best available position for this source is the 3U catalog, from which the error box in Figure 3 is drawn. The only previous optical work on this field has been reported by Bahcall and Bahcall (1974) who found no objects with peculiar colors on the Palomar Sky

Survey prints and no variable objects on two blue plates. We have obtained two pairs of blue and ultraviolet plates with the Crossley reflector. Iris photometry of 100 stars in or near the error box down to $U \approx 18.5$ reveal no stars with an ultraviolet excess, and no variable stars.

i) 3U 1908+00

The best available error box for this source is the 3U catalog. This error box, approximately $1' \times 9'$ in size, is shown in Figure 3. Comparison of ultraviolet and blue Crossley plates for 60 stars in this field revealed no stars with an ultraviolet excess in the error box, but a candidate was found about 4′ away from the edge of the box along the direction of greatest uncertainty in the X-ray position. This object is marked in Figure 3 and listed in Table 2. On one plate (obtained on 1974 May 27) this star appeared to be about 0.3 mag fainter than usual, but the variability has not been confirmed on any of two dozen other plates obtained in 1974 June–September.

We have obtained spectrophotometry of this candidate with the ITS and find that it is an apparently normal B5 V star with $V = 16.0$, $B - V = 0.57$. No evidence for intensity or spectral variations was found over four nights. Assuming $M_v = -1.1$ and $(B - V)_0 = -0.16$ (Allen 1973), this star is at a distance $d = 10$ kpc and has extinction $A_v = 2.2$ mag. It is then 700 pc from the galactic plane, which is unusual for a B star. While this star cannot be regarded as a good candidate for 3U 1908+00 in view of its apparently normal spectrum, our observations do indicate that the reddening in this field is quite modest. An improved X-ray position would therefore be of great value in future efforts to identify this source. X-ray observations obtained with *Copernicus* by the authors in collaboration with P. Sanford and K. Mason show that recently the flux from this source has been much weaker than reported in the 3U catalog.

V. SUMMARY

Application of the criterion that the optical counterpart of an X-ray source should have an ultraviolet excess has led to the identification of candidates for three sources, including both cases where interstellar reddening is low (3U 1709−23 and 3U 1728−16) and one where it is moderate (3U 1908+00). However, the characteristic emission lines of N III λ4640 and He II λ4686, previously common to almost all the confirmed optical counterparts of X-ray sources, have not been definitely detected in any of these objects, nor do they show any strong variability. Thus their association with the X-ray sources remains questionable. Further spectroscopic observations would be useful, however, since these emission features are expected to be variable. Whether or not these candidates are related to the X-ray sources, our results show that interstellar extinction is not likely to prevent the optical identification of these three sources. Therefore, these objects should be given high priority in experiments designed to obtain more accurate X-ray source positions.

Unfortunately, the two sources with the best determined positions have not yielded any definite optical identifications. The only optical object consistent with the lunar occultation X-ray position for 3U 1758−25 is a faint highly reddened early-type object, but no emission lines or peculiar features have been detected. The only optical object consistent with the radio position of 3U 1813−14 is an apparently normal, somewhat reddened G star.

Finally, the infrared candidate for 3U 1728−24 suggested by Glass and Feast (1973) has received further support from the improved X-ray position of Mason (1974). Our observations of the spectrum confirm those of Glass and Feast and also reveal emission features which are probably due to high ionization states of Fe. Such features may be understood if the optical emission arises in a compact nebula which is photoionized by the X-ray source (Davidsen *et al.* 1976).

Perhaps the most surprising result of this survey is that, of the six optical candidates considered, not one appears to be identical to any previously identified compact X-ray source. While one could argue from this result that none of the candidates discussed here is in fact an X-ray counterpart, the possibility that compact X-ray sources may have a wide range of optical appearances should not be too quickly dismissed.

We thank H. Spinrad and J. Liebert for their contributions to this work. Partial support for this research has been provided by NASA grant NSG 7139.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press).
Bahcall, J., and Bahcall, N. 1975, *Proceedings International Conference on X-rays in Space*, Calgary (1974 August), p. 535.
Braes, L., Miley, G., and Schoenmaker, A. 1972, *Nature*, **236**, 392.
Brocklehurst, M. 1971. *M.N.R.A.S.*, **153**, 471.
Cathey, L., and Hayes, J. 1968, *Ap. J.* (*Letters*), **151**, L89.
Ciatti, F., and Rosino, L. 1974, *Astr. and Ap. Suppl.*, **16**, 305.
Crampton, D., and Cowley, A. 1975, *Ap. J.*, **197**, 467.
Davidsen, A., Henry, J., Middleditch, J., and Smith, H. 1972, *Ap. J.* (*Letters*), **177**, L97.
Davidsen, A., and Ostriker, J. 1974, *Ap. J.*, **189**, 331.
Davidsen, A., Malina, R., Smith, H., Spinrad, H., Margon, B., Mason, K., Hawkins, F., and Sanford, P. 1974, *Ap. J.* (*Letters*), **193**, L25.
Davidsen, A., Malina, R., and Bowyer, S. 1976, in preparation.
Davidson, K., and Ostriker, J. 1973, *Ap. J.*, **179**, 585.
Davison, P. J. N. 1973, *Nature Phys. Sci.*, **246**, 90.
Felten, J., and Humphreys, R. 1973, *Ap. J.*, **181**, 543.
Giacconi, R., Gorenstein, P., Gursky, H., Usher, P., Waters, J., Sandage, A., Osmer, P., and Peach, J. 1967, *Ap. J.* (*Letters*), **148**, L129.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., Tananbaum, H. 1974, *Ap. J. Suppl.*, **27**, 37.
Glass, I. S., and Feast, M. W. 1973, *Nature Phys. Sci.*, **245**, 39.

Gottlieb, E. W., Wright, E. L., and Liller, W. 1975, *Ap. J. (Letters)*, **195**, L33.
Hawkins, F., Mason, K., and Sanford, P. 1973, *Nature Phys. Sci.*, **241**, 109.
Hjellming, R. M., and Wade, C. M. 1971*a*, *Ap. J. (Letters)*, **164**, L1.
———. 1971*b*, *ibid.*, **168**, L21.
Jones, C., Chetin, T., and Liller, W. 1974, *Ap. J. (Letters)*, **190**, L1.
Joy, A., and Swings, P. 1945, *Ap. J.*, **102**, 353.
Kraft, R., and Demoulin, M.-H. 1967, *Ap. J. (Letters)*, **150**, L183.
Kunkel, W., Osmer, P., Smith, M., Hoag, A., Schroeder, D., Hiltner, W., Bradt, H., Rappaport, S., and Schnopper, H. 1970, *Ap. J. (Letters)*, **161**, L169.
Lewin, W., Ricker, G., and McClintock, J. 1971, *Ap. J. (Letters)*, **169**, L17.
Margon, B., and Ostriker, J. 1973, *Ap. J.*, **186**, 91.
Mason, K. 1974, private communication.
McClintock, J., Canizares, C., and Tarter, C. B. 1975, *Ap. J.*, **198**, 641.
Murdin, P., Penston, M. J., Penston, M. V., Glass, I., Sanford, P., Hawkins, F., Mason, K., and Willmore, A. 1974, *M.N.R.A.S.*, **169**, 25.
Neckel, T. 1967, *Heidelberg Veröff.*, Vol. **19**.
Oke, J. B., and Sargent, W. 1968, *Ap. J.*, **151**, 807.
Sandage, A., Osmer, P., Giacconi, R., Gorenstein, P., Gursky, H., Waters, J., Bradt, H., Garmire, G., Sreekantan, B., Oda, M., Osawa, K., and Jugaku, H. 1966, *Ap. J. (Letters)*, **146**, 316.
Sandage, A., and Wallerstein, G. 1960, *Ap. J.*, **131**, 598.
Schnopper, H., Bradt, H., Rappaport, S., Boughan, E., Burnett, B., Doxsey, R., Mayer, W., and Watts, S. 1970, *Ap. J. (Letters)*, **161**, L161.
Seyfert, C. K. 1943, *Ap. J.*, **97**, 28.
Tananbaum, H., Gursky, H., Kellogg, E., and Giacconi, R. 1971, *Ap. J. (Letters)*, **168**, L25.
Tarenghi, M., and Reina, C. 1972, *Nature Phys. Sci.*, **240**, 53.
Wallerstein, G. 1962, *A.J.*, **67**, 329.
Webster, B. L., and Allen, D. A. 1975, *M.N.R.A.S.*, **171**, 171.
Willmore, A., Mason, K., Sanford, P., Hawkins, F., Murdin, P., Penston, M. V., and Penston, M. J. 1974, *M.N.R.A.S.*, **169**, 7.
Zaumen, W., Murthy, G., Rappaport, S. Hjellming, R., and Wade, C. 1972, *Nature*, **235**, 378.

Note added in proof.—A dramatic increase of the flux of Aql X-1 occurred in 1975 June (Buff, IAU Circ. No 2788). No corresponding optical flare was detected (Davidsen *et al.* IAU Circ. No. 2793).

New positions for four of the X-ray sources discussed above have recently been derived from SAS-3 observations (Doxsey, IAU Circ. No. 2820). The positions obtained for GX 9+9 and GX 17+2 are consistent with the candidates discussed here. The new positions for Ser X-1 and Aql X-1 are outside the 3U error boxes. The B5 V star near Aql X-1 is also not included in the new error box.

STUART BOWYER and ROGER MALINA: Space Sciences Laboratory, University of California, Berkeley, CA 94720

ARTHUR DAVIDSEN: Department of Physics, The Johns Hopkins University, Baltimore, MD 21218

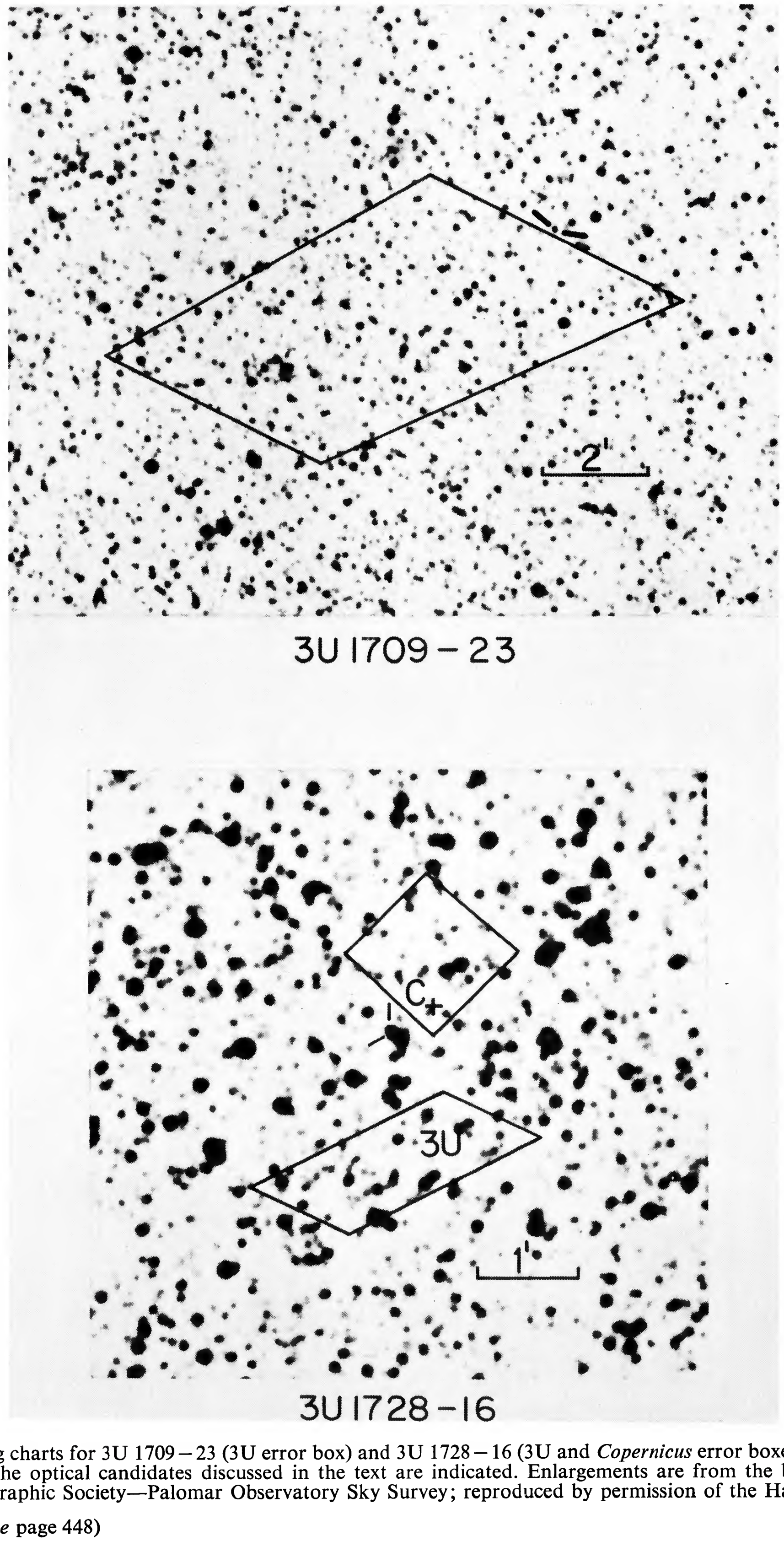
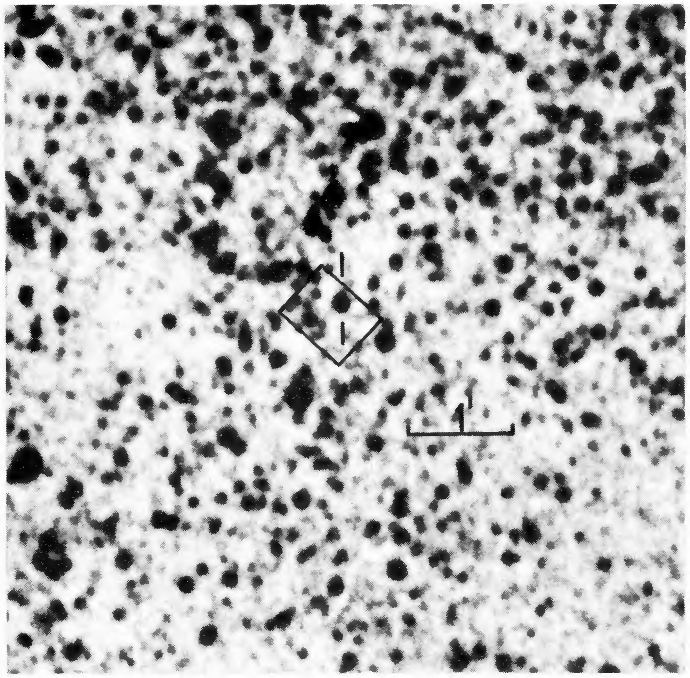
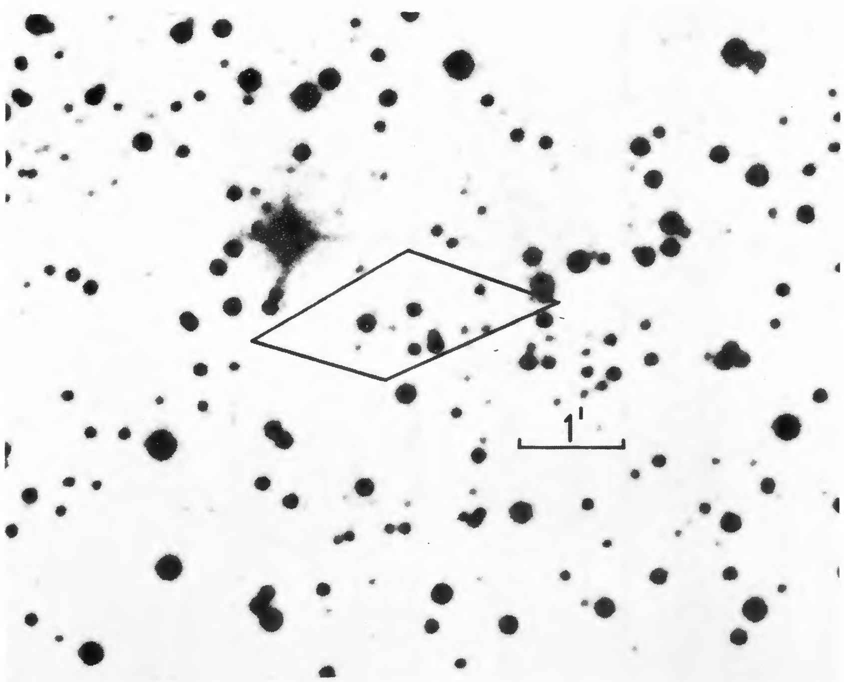


FIG. 1.—Finding charts for 3U 1709 − 23 (3U error box) and 3U 1728 − 16 (3U and *Copernicus* error boxes). North is at the top; east, to the left. The optical candidates discussed in the text are indicated. Enlargements are from the blue Sky Survey plates (© National Geographic Society—Palomar Observatory Sky Survey; reproduced by permission of the Hale Observatories).

DAVIDSEN *et al.* (*see* page 448)



3U 1728 – 24



3U 1811 – 17

FIG. 2.—Finding charts for 3U 1728 − 24 (*Copernicus* error box, red Sky Survey plate) and 3U 1811 − 17 (3U error box, blue Sky Survey plate). North is at the top; east, to the left. The optical candidate for 3U 1728 − 24 is indicated.

DAVIDSEN *et al.* (*see* page 448)

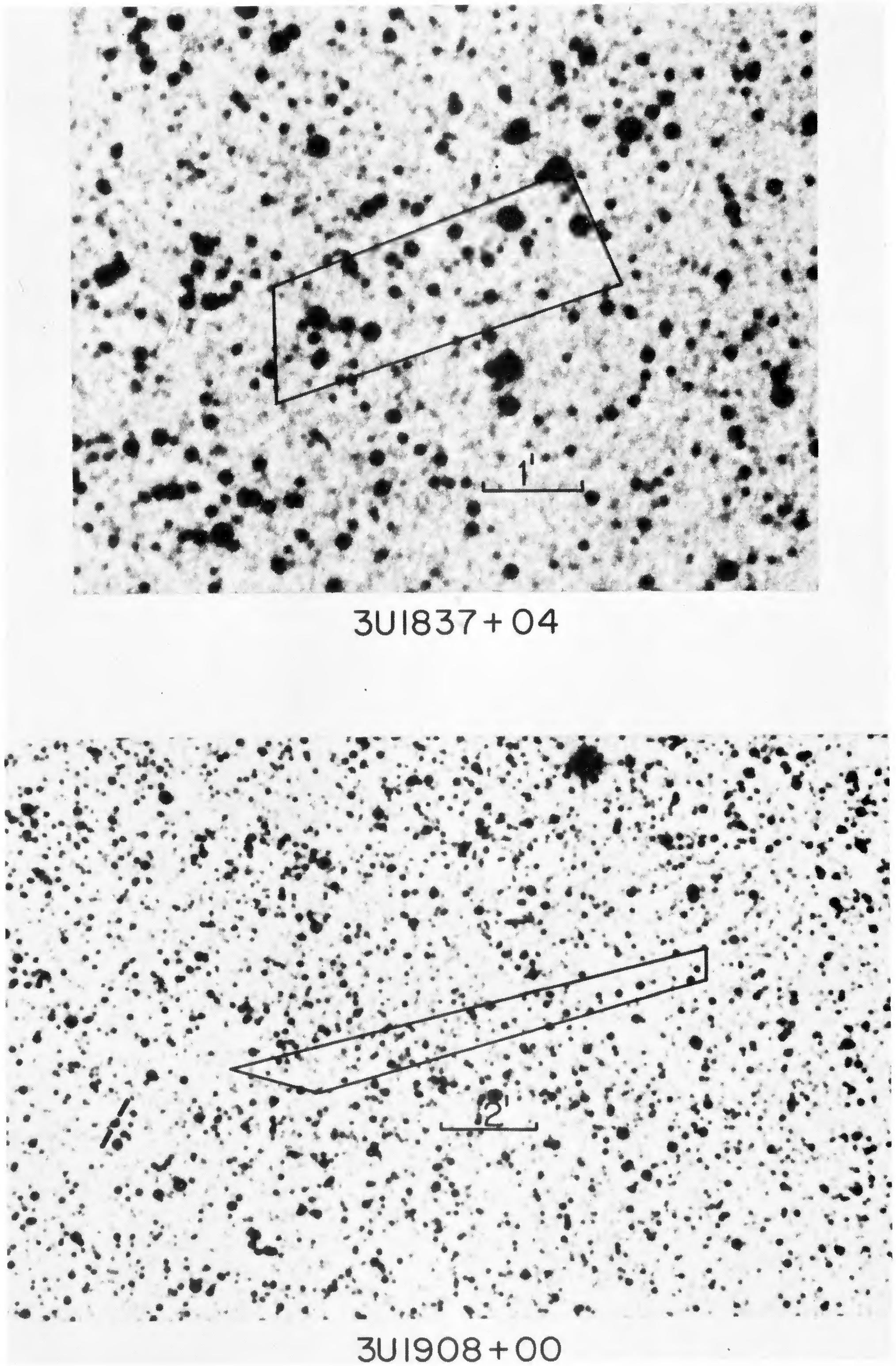


FIG. 3.—Finding charts for 3U 1837+04 and 3U 1908+00. Both error boxes are from the 3U catalog. Enlargements are from the blue Sky Survey plates. North is at the top; east, to the left. The optical candidate for 3U 1908+00 is indicated.

DAVIDSEN *et al.* (*see* page 448)