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TWO MORE GLOBULAR CLUSTER X-RAY SOURCES?

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ABSTRACT

Both the variable X-ray source 4U 0026−73 and the X-ray burst source XB 1724−31(=4U 1722−30?) may be identified with, respectively, the globular clusters Kron 3 and Terzan 2. Both of these clusters were "rediscovered" with observations at CTIO. If confirmed, these identifications increase the number of X-ray globulars to at least nine, of which at least five or six are bursters. The Kron 3 identification would be the first Magellanic Cloud–type globular cluster X-ray source. The Terzan 2 identification may imply that the globular cluster is being disrupted, perhaps due to the combined effects of tidal stripping and a central black hole.

Subject headings: clusters: globular — X-rays: bursts — X-rays: sources

I. INTRODUCTION

At present there are at least seven known globular cluster X-ray sources (cf. review of Grindlay 1977). The locations of six of these are well established and are known to be well within the cluster tidal radius and probably within the core (Jernigan and Clark 1978; Doxsey *et al.* 1978). We suggest here that two additional X-ray sources, including a burst source, may also be probably identified with globular clusters. In each case the (previously reported) X-ray error box includes the globular cluster. We report optical measurements of the two new clusters for comparison with other X-ray globulars and find interesting implications for both the X-ray sources and cluster structure.

II. IDENTIFICATION OF 4U 0026−73

The X-ray source at or near the 4U 0026−73 position (Forman *et al.* 1978) is near the variable sources SMC X-2 and SMC X-3 found later by *SAS 3* (Clark *et al.* 1978). However, a point summation technique (PST) analysis showed that neither SMC X-2 nor SMC X-3 was present in the *Uhuru* data at $\gtrsim 1$ *Uhuru* flux unit (UFU) (or comparable to the PST intensity for 4U 0026−73). Independent evidence for the existence of 4U 0026−73 has been obtained by PST analysis (excluding the SMC sources) of *Ariel 5* SSI data (Ricketts 1978). This yielded a source strength of $\sim 0.33 \pm 0.12$ *Ariel* counts s^{-1} (or ∼1 UFU) which was reasonably constant during six scans over the source in 1975–1976. The combined *Uhuru* and *Ariel 5* data (as well as the *SAS 3* upper limit [Clark *et al.* 1978]) are thus consistent with a ∼1–2 UFU source at the 4U 0026−73 position.

While preparing finding charts for our 1977 August observations at CTIO, we noticed that the overlay of the 4U 0026−73 error box (Forman *et al.* 1978) on the *ESO B* survey included (nearly) two stellar clusters (cf. Fig. 1). These were found to be Kron 3 and Kron 7 (Kron 1956; Gascoigne and Kron 1952), of which only the first is definitely a globular cluster. Both clusters are probably associated with the Small Magellanic Cloud (SMC); in fact, detailed measurements of the H-R diagram for Kron 3 (Gascoigne 1966; Walker 1970) indicate that its distance modulus is $m - M \approx 19.1$ as is found for the other SMC clusters (Gascoigne 1966). Given the number of globular clusters ($\gtrsim 16$) near the SMC (Kron 1956), the random probability that $\gtrsim 1$ is in the error box is less than 10%. Optical studies reported here make the identification with Kron 3 even more certain.

Kron 3 is in fact one of the better observed globular clusters and has been labeled as of intermediate age and similar to the galactic globulars M13 or NGC 2158 by Gascoigne (1966). However, Walker (1970) concludes that Kron 3 may in fact be metal-rich like NGC 6356. He also makes the interesting observation that the brightest red giants are not concentrated in the cluster core but are more evenly distributed—an observation which may indicate these stars underwent an *earlier* mass loss phase and are now reentering the giant phase for the second time. The brightest red giants in Kron 3 are redder (with $B - V \approx 2.2$) than stars at the tip of the giant branch in Galactic globular clusters; this is a distinctive feature of Kron 3 and several other SMC globulars (Gascoigne 1966; van Den Bergh 1968; Danziger 1973). We have not found similar studies of Kron 7, probably because it is so diffuse and is not even classified as a globular by Kron (1956). Its proximity to Kron 3 suggests that it may have formed as a fragment of the same original cloud; other cluster pairs in the SMC–LMC have been pointed out by Gascoigne (1966). We shall summarize our broad-band photometry of Kron 3, as well as Kron 7, to determine which is the more likely identification of 4U 0026−73.

Photometry of both Kron 3 and Kron 7 was done on the 1.5 m telescope at CTIO on 1977 August 15. Broad-band photometry in *UBVR* and narrow-band

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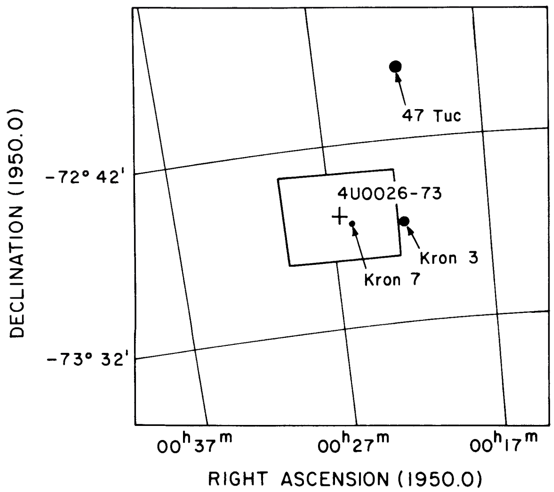

FIG. 1.—Error box (90% confidence) of 4U 0026−73 (Forman *et al.* 1978) and the location of its probable counterpart, the SMC globular cluster Kron 3. The companion (?) diffuse cluster Kron 7 and the galactic globular cluster 47 Tuc are also indicated.

(16 Å and 85 Å) photometry in Hα were carried out with concentric diaphragms visually centered on the cluster core as in the globular cluster studies of Grindlay and Liller (1977). Results for both clusters are given in Table 1. Our results for Kron 3 are in good agreement with those of van den Bergh (1968), who used only a 60″ diaphragm, except that our $U - B$ colors are ~0.05 mag redder. We note that there are not significant color gradients in Kron 7 but that there is a marginally significant (~2σ) color gradient in $(B - V)$ for Kron 3 with a bluer $[\Delta (B - V) \lesssim 0.1$ mag] core (see below). In Kron 3, it is also especially interesting that the Hα indices (cf. Grindlay and Liller 1977) H16/*R* and H16/H85 are somewhat larger within the central ~10″ core than in the cluster as a whole. Although the H85 flux is low (by ~2σ), this may suggest weak Hα emission in the core (as was also found for four of the five X-ray globulars observed by Grindlay and Liller 1977 and supports the identification of Kron 3.

We have obtained *U* and *B* images (cf. Fig. 2 [Pl. L6]) of both clusters with the CTIO 4 m telescope on 1977 August 27. It is obvious that Kron 7 has no defined core but that Kron 3 has a well-defined core (especially evident in *U*). The diffuse distribution of red giants discussed by Walker (1970) is also evident in our *B* exposure and can account for the possible $(B - V)$ gradient. We have therefore used our *U* magnitude surface brightness data (Table 1) for Kron 3 to estimate a King (1966) model for the integral surface brightness distribution. This, together with the data of Table 1, an assumed distance of ~66 kpc, and $A_V \approx 0.1$ (Gascoigne 1966), enables us to use the analysis of Peterson and King (1975) and Canizares *et al.* (1978) to estimate the relevant parameters for Kron 3: concentration parameter $C < 1.7$, core radius ~17″ (~5 pc), and central density $\rho_0 \sim 10^2\ M_\odot\ \mathrm{pc}^{-3}$ (assuming $M/L \approx 1$). Thus Kron 3 is not like the centrally condensed X-ray globulars (e.g., NGC 6624) and is even more diffuse than the one previously known "loose" X-ray globular, NGC 6712 (see Grindlay 1977 for a review) and is therefore also a candidate for an X-ray globular undergoing disruption. Kron 7, for which a King model cannot be fitted from our photometry but could be fitted from star counts, must have (estimating a core radius ~25″ and using Table 1) a density $\rho_0 \lesssim$ 10–30 $M_\odot\ \mathrm{pc}^{-3}$, and a globular cluster identification is not justified.

The *U* and *B* plate (cf. Fig. 2) was carefully searched for any objects in or near the error box which were brighter in *U* than *B;* none were found. We thus conclude that Kron 3 is the likely identification of 4U 0026−73. The X-ray luminosity of 4U 0026−73 at the distance of Kron 3 is $L_X \approx 10^{37}$ ergs s^{-1}, which is comparable to the Galactic globular cluster sources (Grindlay 1977) and not abnormally luminous as are the (metal-poor?) SMC X-ray binaries (Clark *et al.* 1978).

III. IDENTIFICATION OF XB 1724−31 (=4U 1722−30?)

As part of our program to search for obscured or disrupted globular clusters predicted (Grindlay 1978) to be the optical counterparts of at least some X-ray

TABLE 1

PHOTOMETRY OF KRON 3 AND KRON 7

Diaphragm	*V*	*B−V*	*U−B*	*V−R*	H16/*R*	H85/*R*	H16/H85
				Kron 3			
6″.7..........	15.98	0.56	0.18	0.49	0.001(.003)	0.033(.004)	0.035(.084)
10″.7..........	14.96	0.65	0.17	0.49	0.005(.001)	0.031(.002)	0.158(.046)
25″.1..........	13.29	0.67	0.17	0.52	0.003(.001)	0.033(.001)	0.083(.018)
50″.7..........	12.03	0.70	0.20	0.58	0.002(.003)	0.030(.0006)	0.071(.011)
				Kron 7			
10″.7..........	15.40	0.62	0.09	1.01	0.005(.003)	0.031(.005)	0.166(.087)
25″.1..........	14.72	0.83	0.19	1.04	0.006(.002)	0.021(.004)	0.278(.119)
50″.7..........	14.04	0.73	0.11	0.74	0.006(.003)	0.027(.006)	0.203(.125)

NOTE.—The errors in *V* and the broad-band colors $B - V$, $U - B$, and $V - R$ are ~0.10 mag and ~0.05 mag for observations with the 6″.7 and ≥10″.7 diaphragms, respectively.

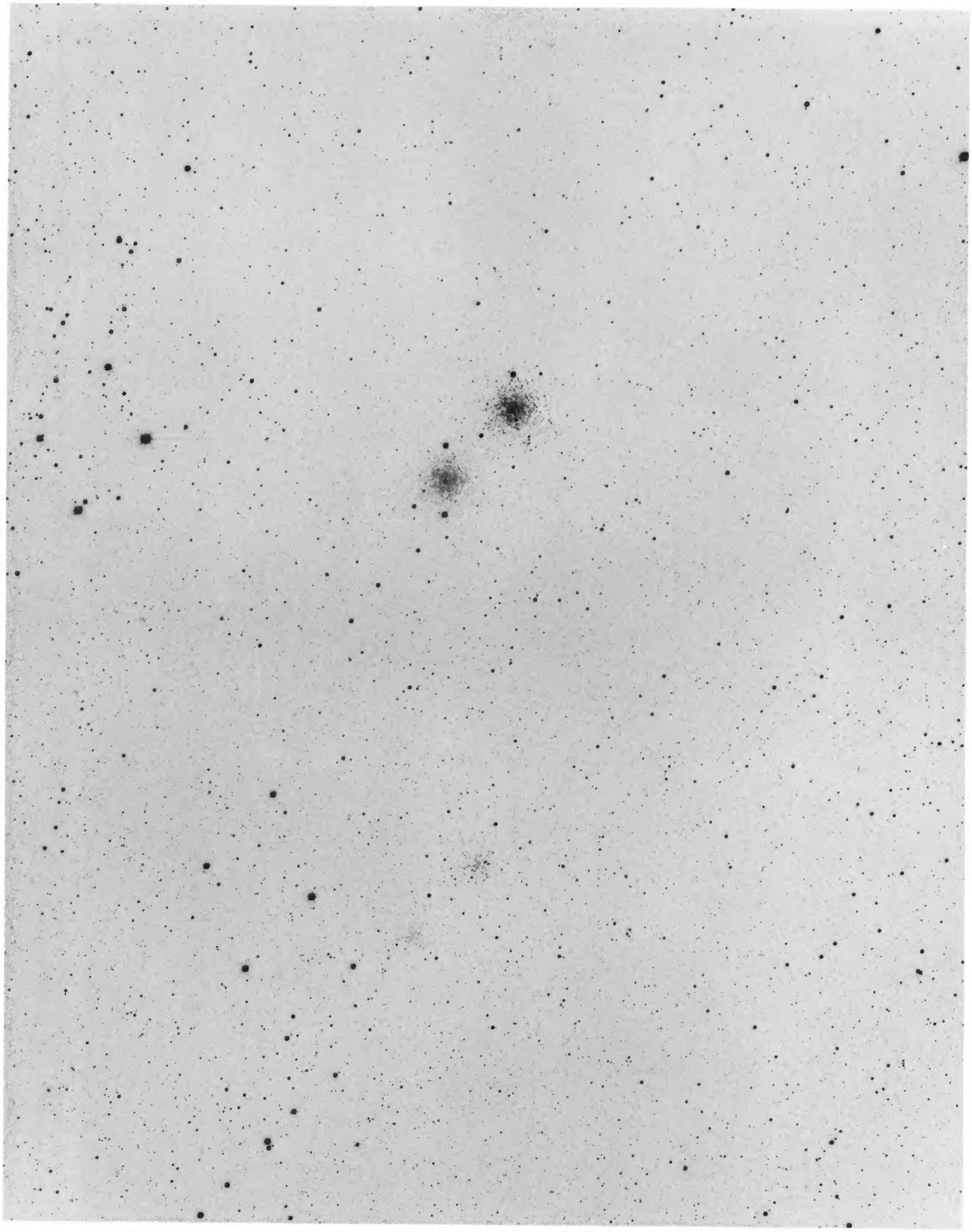

FIG. 2.—Double exposure photograph in U and B of the field containing Kron 3 (*right*), which is the probable identification of the X-ray source 4U 0026−73, and Kron 7. The 103a-O plate was obtained with the CTIO 4 m telescope on 1977 August 26 and exposed 25 min in U (UG-2 filter, upper image) and 6 min in B (GG385 filter). North is up, east is left, and the print scale here is $\sim 10'' \text{ mm}^{-1}$.

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burst sources, we obtained on 1977 August 25 a deep (1 hour exposure) IV-N plate (with RG-695 filter) with the CTIO 4 m telescope on a 1° field containing a burster discovered by Swank *et al.* (1977). Those authors reported *OSO 8* observations of a single long X-ray burst, with rise time ≤ 10 s and decay time ~ 100 s, and an apparently associated steady source located near $l^{II} = 356\overset{\circ}{.}4$, $b^{II} \approx 2\overset{\circ}{.}3$. Though Swank *et al.* did not name this source but noted it could be *Uhuru* source W (Forman, Jones, and Tananbaum 1976), we adopt the usual convention and will refer to this burster and persistent source as XB 1724−31. The *OSO 8* 90% confidence level error boxes (Swank *et al.* 1977) for the burst source and weak persistent source intersect in a region of area $\sim$0.09 square degrees (cf. Fig. 3). We were thus very surprised to find (at CTIO) an apparently "new" globular cluster within this small region of the IV-N plate (cf. Fig. 4 [Pl. L7]); further investigation (in Cambridge) revealed that this globular had been discovered previously by Terzan (1967) and is in fact called Terzan 2 (Terzan 1971).

Using the expression for the spatial density of Galactic globular clusters versus angular distance from the galactic center given by Clark, Markert, and Li (1975), the random probability that a known globular cluster should be within the combined *OSO 8* error box (cf. Fig. 3) is only $\sim 8 \times 10^{-3}$. The chance coincidence probability is still $\lesssim 1.5\%$ when the distribution of all (11) known obscured globulars near the galactic center (Terzan 1971; Liller 1977) is added to the overall galactic distribution, so we conclude that XB 1724−31 is very likely identified with Terzan 2.

It is also possible that 4U 1722−30, or a neighboring *Uhuru* source (either of which could account for source W), is in fact XB 1724−31 = Terzan 2. In Figure 3 we also plot the 90% confidence region from which the rectangular error box given in the 4U catalog (Forman *et al.* 1978) for 4U 1722−30 was derived. With the assistance of C. Jones, it was found that two lines of position used to determine the source latitude *could* have been contaminated by the galactic center transient source A1743−29 (Jernigan *et al.* 1978). If these two lines are omitted from the total (20) used, the *Uhuru* 90% confidence location is given by the dashed contour in Figure 3. However, for the transient source to have had a significant effect on the 4U 1722−30 position, it would have to have been $\gtrsim 50$ *Uhuru* counts s^{-1} during the two suspect observations. Although these scans were made within 2 days of each other and a flare is possible, an upper limit of $\sim$20–30 *Uhuru* counts s^{-1} is estimated (C. Jones, private communication) for a source at the position of the transient A1743−29 in the remainder of the *Uhuru* data base. Thus the identification of XB 1724−31 or Terzan 2 with an *Uhuru* source, i.e., either a revised position for 4U 1722−30 or a nearby weak source, must be confirmed by higher-resolution experiments such as *HEAO 1* or *HEAO B*.

We have estimated the reddening and extinction toward Terzan 2 by comparing iris photometry of cluster stars visible on the IV-N plate versus the Palomar Sky Survey red and blue prints. We measured approximate I and R magnitudes of 18 stars in or around the cluster core; only nine of these were visible in B (and many of these may be foreground stars since the cluster is not recognizable on the POSS O print and only just distinguishable on the POSS E print). The POSS analysis gave a lower limit for the apparent color, $(B - R) \geq 3$. Assuming the cluster has intrinsic colors like NGC 6624 for which $(B - R)_0 \approx 1.4$ (Canizares *et al.* 1978) and using a normal reddening law (Allen 1973), we then obtain a lower limit on the extinction $A_v \gtrsim 3$. Comparison of the approximate R and I magnitudes yields a mean apparent $(R - I) \approx 1.3$; and comparison with NGC 6624 and the reddening law then gives $A_v \approx 4$. As a third estimate, we note that the reddest and brightest stars in the core (cf. Fig. 4) are

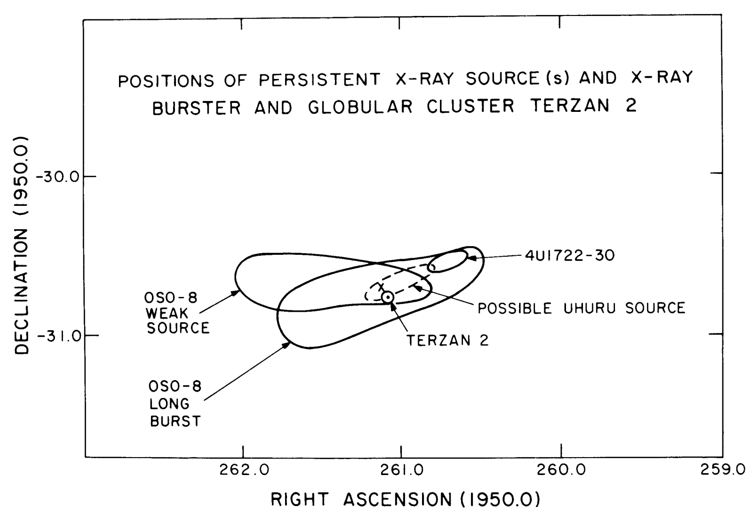

FIG. 3.—Locations (90% confidence) of X-ray burster (the × gives the most probable position) and associated (?) persistent source XB 1724−31 detected by *OSO 8* (Swank *et al.* 1977) and the probable globular cluster counterpart, Terzan 2. The cataloged position of 4U 1722−30 (Forman *et al.* 1978) would shift to the dashed contour if a nearby transient source (A1743−29) contaminated two *Uhuru* data sets or there are two weak sources in the region.

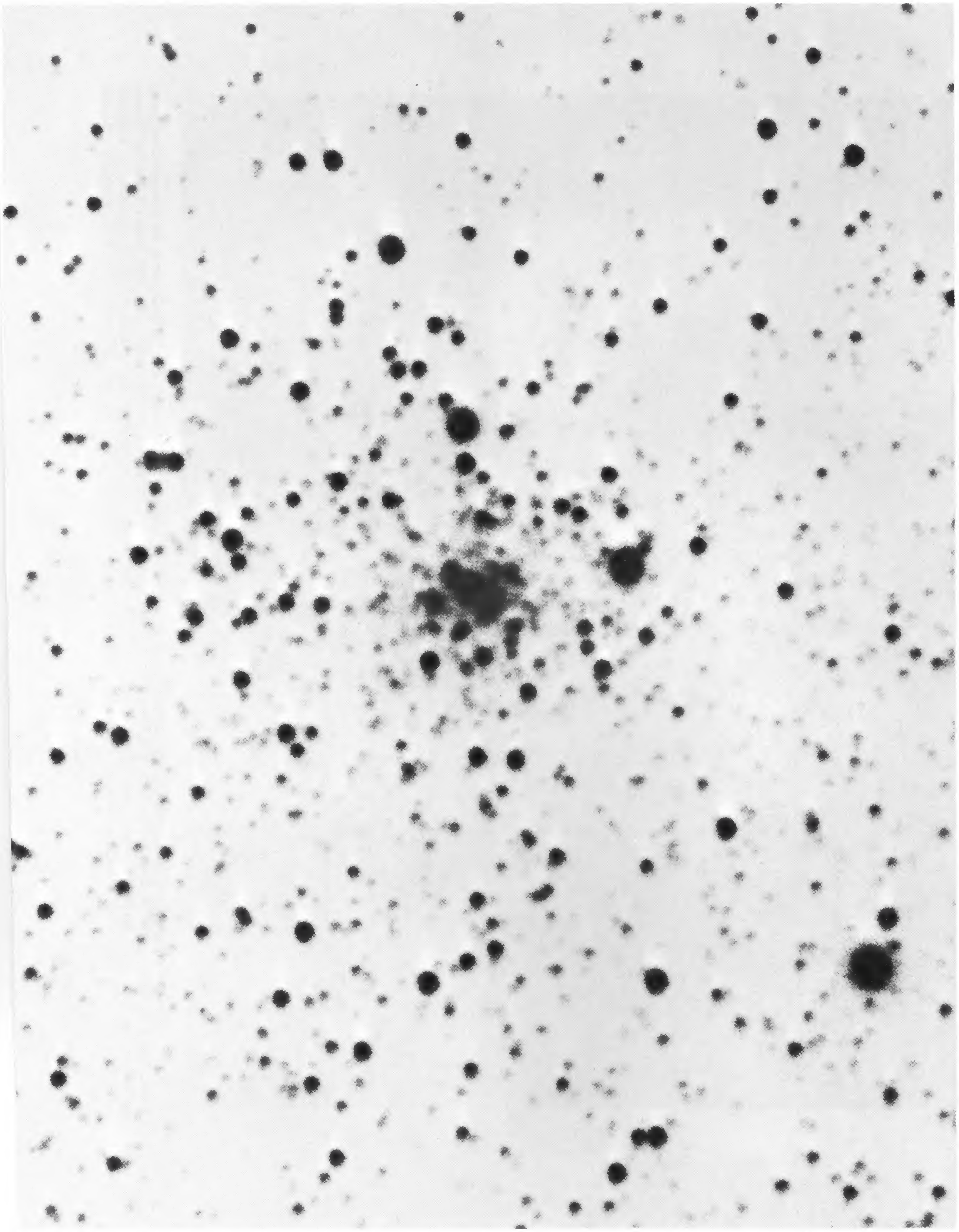

FIG. 4.—Enlargement (16×, or ~1″.2 mm^{-1}) of a deep plate in I (approximately) showing the globular cluster Terzan 2, the probable identification of the X-ray burst source XB1724−31. The plate is a sensitized (with $AgNO_3$) IV-N plate exposed for 1 hour through a RG695 filter, using the CTIO 4 m telescope on 1977 August 25. North is up, east is left.

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not visible [i.e., $(B - R) \gtrsim 5$] on the POSS O print. Assuming that these are red giants near the tip of the cluster giant branch with $(B - V)_0 \approx 1.5$–2 (as for NGC 6624; cf. Liller and Carney 1978), the reddening law gives $A_v \approx 5$. Finally, we note that the usual galactic reddening law adopted (e.g., Peterson and King 1975) for globular clusters gives $A_v \approx 0.15 \csc b^{\rm II} \approx 3.8$. Thus our four estimates of the extinction toward Terzan 2 are in reasonable agreement and suggest that $A_v \approx 4$–5 mag.

Adopting $A_v \approx 4$ and our mean apparent $\langle m_R \rangle \approx 16$ for the 18 brightest stars in Terzan 2, we again assume intrinsic colors like NGC 6624 and use the usual cluster relation (e.g., Peterson and King 1975) that $\langle M_B \rangle \approx -0.7$ for the average of the 25 brightest stars to estimate the cluster distance is $d \approx 7 \pm 3$ kpc. The error is approximate but includes the uncertainties in A_v, intrinsic color, and the magnitude estimates. The measured persistent source and X-ray burst (peak) fluxes (Swank *et al.* 1977) would then imply X-ray luminosities $L_{\rm steady} \approx 2(+2, -1) \times 10^{36}$ ergs s^{-1} and $L_{\rm burst} \approx 3(+4, -2) \times 10^{38}$ ergs s^{-1}. These are in the range for other X-ray globular clusters (Grindlay 1977), though the burst luminosity may be somewhat higher. Since $A_v \approx 4$ would approximately correspond to a column density $N_{\rm H} \approx 9 \times 10^{21}$ cm^{-2} (Gorenstein 1975), the *OSO 8* spectrum (measured at $\sim$2–20 keV) for the persistent source—which gave $kT \approx 10 \pm 2$ keV and $N_{\rm H} \approx 1.8 \pm 1.8 \times 10^{21}$ cm^{-2} (Swank *et al.* 1977)—may imply that the persistent source also includes an underlying soft component which effectively reduces the $N_{\rm H}$ value inferred from the X-ray spectrum. Similarly discrepant X-ray versus optical $N_{\rm H}$ values are found for Cyg X-1 and Cyg X-2 (Gorenstein 1975). The burst spectrum (Swank *et al.* 1977), however, gives an $N_{\rm H}$ value which may exceed the optical value, implying that there is excess absorption and/or that any soft component is relatively smaller during bursts.

Finally we return to the structure of Terzan 2 as compared to other X-ray globulars. From the IV-N plate (Fig. 4), we estimate the core radius $\theta_c \approx 5''$ or $r_c \approx 0.2$ pc given the distance estimate. Thus the cluster is very compact in its core and probably not of Shapley-Sawyer class XI–XII as estimated from the early I-N plate by Terzan (1967). In fact, since the bright group of stars in the core has an apparent magnitude $I \approx 12$, we estimate [using $A_v \approx 4$ and an assumed $(V - I)_0 \approx 1$] the central surface brightness is $\sigma_v \sim 6$–7 mag arcmin^{-2} if there were no extinction. This is comparable to that measured for NGC 6624 (Canizares *et al.* 1978), so the central stellar density may also be comparable and in the approximate range 10^4–10^5 $M_\odot$ pc^{-3}. Since the central density and distance of Terzan 2 seem to resemble NGC 6624, it is instructive to consider if in fact NGC 6624 with $A_v \approx 4$–5 (instead of $A_v \approx 1$) would look just like Terzan 2 in its stellar density or surface brightness *outside* the core. For NGC 6624 we found (Canizares *et al.* 1978) that without extinction, $\sigma_I \approx 12.6$ mag arcsec^{-2} in an annulus $15'' \leq \theta \leq 20''$ outside the core. This would translate to $\sigma_I \approx 18.2$ mag arcsec^{-2} for Terzan 2, given our derived parameters. Unless the extinction were much greater than the largest value ($A_v \approx 5$) of the four estimates we made, this predicted value of σ_I is at least $\sim$2 mag brighter than the observed surface brightness $\sigma_I \sim 20$ mag arcsec^{-2} for the annulus on our IV-N plate. Note that larger extinction for Terzan 2 would both increase the discrepancy with the X-ray value of $N_{\rm H}$ and move the cluster closer to us, which would increase the discrepancy in halo brightness since then the $15''$–$20''$ annulus on Terzan 2 should correspond to a smaller and still brighter annulus on NGC 6624. On the other hand, if the core of Terzan 2 is intrinsically redder than NGC 6624, the discrepancy in relative halo brightness would be reduced. Infrared colors versus core radius are needed for both clusters. Thus we conclude that there is some evidence that Terzan 2 has a halo that is more diffuse than its apparently condensed core would indicate. This could indicate significant tidal stripping of Terzan 2, which might be expected, given its location near the galactic center. The obscured X-ray globular Liller 1 (Liller 1977), for which we also obtained a 1 hour IV-N plate, looks very much like Terzan 2, and studies are in progress (Feigelson and Grindlay 1978) to determine if it might also be tidally stripped.

III. DISCUSSION

The identification of two more globular cluster X-ray sources would increase the total of such sources to at least nine. The suggested identifications include the first extragalactic (and possibly disrupted) globular cluster source (Kron 3) as well as a candidate for a tidally stripped cluster core source (Terzan 2). Given the variability of all these sources and the obscured nature of clusters like Terzan 2, many more cluster sources may be found. It is significant that one of the two new cluster sources may also be a burster. Since then five (and possibly six if the X-ray cluster NGC 6712 is identified with an *OSO 8* burst source [Swank *et al.* 1976]) of the eight globular cluster X-ray sources in the Galaxy would also be bursters, a special condition must exist in cluster cores which favors burst production. If this is a condition on the orbital elements or stellar composition of low-mass close binaries (cf. Lewin and Joss 1977 for a review of these burster models) formed in globulars, then it is not obvious why possibly similar systems (e.g., Sco X-1) not in globular clusters do not burst. On the other hand, if accretion onto a $\sim$10–100 $M_\odot$ black hole is required for a burster (Grindlay 1978), then cluster cores are a likely site. The possible blackbody-cooling spectra of bursters like XB 1724$-$31 (Swank *et al.* 1977) do not eliminate $\sim$10–100 $M_\odot$ black holes if realistic emissivities (<1) are included. Since globular clusters containing black holes (or tight binaries) might evaporate stars and thus be tidally stripped more readily (cf. Shapiro 1977; Grindlay 1977), it may be significant that Terzan 2 (and possibly Liller 1?) and NGC 6712 are all candidates for clusters undergoing disruption. The extreme case in this picture would then be an isolated remnant black hole which can be detectable as an X-ray source and burster when it passes through a moderately dense interstellar cloud (Grindlay 1978). The faint blue optical candidate for the burster MXB 1735−44 (McClintock, Canizares, and Backman 1978) could in fact be such an object, since the striking similarity of the emission line spectrum (though there is a lack of variability and Balmer emission) to Sco X-1 *only* means the system contains X-ray heated gas and does not require the geometry of a close binary.

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