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X-RAY OBSERVATIONS OF GLOBULAR CLUSTERS WITH ANS

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ABSTRACT

Pointed observations were resumed with ANS during 1976 March–April to search for both steady and burst X-ray emission form globular clusters. No new sources were found among the 16 clusters observed, and significant upper limits and required variability ranges are reported. Bursts were detected from MXB 1730−335, and steady emission (but no bursts) was detected from both NGC 6624 and the source A1850−08 near the diffuse globular cluster NGC 6712. The improved ANS position for this latter source is $4' \pm 3'$ (90% confidence level) south of the cluster, and the combined ANS–*Uhuru–Ariel* 5 error box ($\sim 12' \times 4'$) is centered SE of the cluster and includes several variable stars outside the cluster. However, since the core cannot be excluded, NGC 6712 could resemble the centrally condensed cluster sources (possibly containing massive central objects) if the cluster is being disrupted.

Subject headings: clusters: globular — stars: variables — X-rays: sources

I. INTRODUCTION

The X-ray sources found in some globular clusters (e.g., Giacconi *et al.* 1974; Clark, Markert, and Li 1975) may provide insight into both our understanding of accretion X-ray sources and the evolution of globular cluster stellar systems. One of these X-ray sources (3U 1820−30 = NGC 6624) was the first to be identified as a bursting X-ray source (Grindlay *et al.* 1976). This suggests that these objects could be distinctly different from the (nonbursting?) binary X-ray sources like Sco X-1, which might form (e.g., Hills 1975) from the low-mass stars in globular clusters. At present there are five possible identifications of X-ray sources with globular clusters which all have very high central densities (Bahcall and Hausman 1976). Where the uncertainties in the X-ray source positions are smallest ($\lesssim 1'$ for NGC 6624 and M15 [Jernigan 1976]) the source location includes the cluster core. A sixth cluster source was found with the discovery (Liller 1976) of a globular cluster (Kleinmann, Kleinmann, and Wright 1976) of very high central density at the position of the rapid burster MXB 1730−33 (Lewin *et al.* 1976). We shall report results of pointed observations of 16 globular clusters with the Astronomical Netherlands Satellite (ANS). No new sources were found in this survey, and significant upper limits were obtained for 11 clusters as well as for two of the previously identified X-ray globular clusters. Many of these 11 clusters not detected as X-ray sources appear optically to be as centrally condensed as the X-ray clusters.

A new source (A1850−08) whose error box included the diffuse globular cluster NGC 6712 was found by *Ariel 5* (Seward *et al.* 1976). The *Uhuru* detectors recorded a flare from this source (Cominsky *et al.* 1977) and "steady" emission (although variable) on several occasions that was comparable to that observed by *Ariel 5*. The *Uhuru* data yielded an improved source position which also includes the globular cluster NGC 6712. If this cluster identification were confirmed, it would be a significant departure from the usual association of X-ray sources with high-central-density clusters and the consequent models for "heavy" binaries (e.g., Hills 1975) or massive black holes (Bahcall and Ostriker 1975; Silk and Arons 1975) at the cluster center. We report an improved position for this X-ray source: the center of the new error box is offset from the center of the cluster and may suggest identification with a field variable star. However, the cluster core is also still contained in the 90% confidence source location region. If this is in fact the source location, NGC 6712 may be an example of a (partially) disrupted cluster that could leave a massive core remnant as suggested (Grindlay 1977*a*) for the X-ray bursters.

II. GLOBULAR CLUSTER OBSERVATIONS

Our results were obtained during a 6-week period in 1976 March–April, when the X-ray detectors on ANS resumed pointed observations. The primary objectives of the observations were to search for new sources of X-ray bursts in globular clusters (such as the source in NGC 6624), to improve positions (as of 1976 March) of bursters identified by SAS-3 (see Grindlay 1976; Lewin 1976*a* for reviews) and to search for steady X-ray emission from new globular clusters. Observations were, typically, pointings of ~5–10 min duration on a given object for each 98 min orbit. Approximately 70% of the observations were continuous pointing (within $\pm 0'.5$) on the object to maximize exposure for bursts; the remainder were done in the offset pointing mode whereby the satellite alternately pointed 64 s on source and 64 s off for local background determination. The X-ray detectors on ANS used in these observations were the Utrecht (Brinkman, Heise, and De Jager 1974) soft X-ray (SXX) detector ($\sim$1–7 keV) and the two SAO (Gursky, Schnopper, and Parsignault 1975) hard X-ray detectors ($\sim$1–28 keV). The detectors have comparable sensitivities (1 ct $s^{-1} \approx$ 15 ct s^{-1} for *Uhuru* assuming an X-ray spectrum like that of the Crab Nebula) in the $\sim$1.4–7.2 keV range and coaligned fields of view (FWHM) of $35' \times 84'$ (SXX) and $10' \times 3°$ (HXX). The two HXX detectors are offset by $3'.7$ so that accurate positions (in one dimension) may be obtained (e.g., Grindlay *et al.* 1976; Heise *et al.* 1976) from the ratio of counts detected in both counters.

A total of 16 globular clusters were selected for observation from the data compiled by Peterson (1976) and Peterson and King (1975). In accordance with known cluster sources, we chose clusters with the highest central densities, escape velocities, and/or shortest relaxation times subject to visibility constraints of the satellite. Several diffuse globular clusters (e.g., NGC 2298, NGC 6712, and NGC 6779) were also included. Six of our clusters had previously been observed by *Uhuru* in 1971, yielding (for that epoch) the upper limits reported by Ulmer *et al.* (1976). The known bursters observed in an effort to detect bursts and improve positions were the Norma burster position (Grindlay and Gursky 1976), the rapid burster MXB 1730−33 (Lewin *et al.* 1976), and several regions near ($<0°.5$) the galactic center containing several bursters (Lewin 1976). The total exposure on each object was typically $\sim$2 hr spread over $\sim$3 days of observations.

No new bursters were discovered in our observations but several series of bursts were detected from MXB 1730−33. These observations produced a significantly improved source position (Heise *et al.* 1976) and strengthened the identification with Liller's globular cluster. Steady emission was observed (1976 March, $\sim$23.3–24.2) from NGC 6624 at the $\sim$210 *Uhuru* count level, indicating that the source was in a "high state" and therefore probably not bursting (Grindlay *et al.* 1976; Clark *et al.* 1976); and indeed no bursts were observed. The only other significant detection of steady X-ray emission was from A1850−08 near NGC 6712, which we shall describe below. The remaining globular clusters yielded the upper limits given in Table 1.

The ANS upper limits are typically a factor of $\sim$2 lower than the limits obtained by *Uhuru* (Ulmer *et al.* 1976) for the clusters marked by (U); for one case (NGC 6760), the ANS limit is a factor of $\sim$10 lower. Sustained (> days) or "steady" X-ray emission has been observed on occasion from sources possibly identified with NGC 1851 (Clark *et al.* 1975) and NGC 6640 (detected for only $\sim$1 month [Forman, Jones, and Tananbaum 1976]); our upper limits are significantly below the minimum flux levels reported. For both these

TABLE 1

RESULTS OF GLOBULAR CLUSTER SURVEY WITH ANS

Object	Observed Rate (ct s^{-1}) (1–7 keV)	3σ Upper Limits: Rate (ct s^{-1})	3σ Upper Limits: L_x (10^{36} ergs s^{-1})	Cluster Parameters*: R (kpc)	Cluster Parameters*: ρ_c (10^4 $M_\odot$ pc^3)	Cluster Parameters*: V_e (km s^{-1})	Cluster Parameters*: T_R (10^7 yr)
NGC 1851	0.06±0.04	0.12	0.41	11.0	8.5	35	3.7
1904	−0.01±0.04	0.12	0.55	12.7	0.4	19	15
2298	0.03±0.03	0.09	0.39	12.4	0.06	12	23
6266 (U)	0.00±0.04	0.12	0.21	7.9	3.6	33	8.0
6341 (U)	−0.12±0.07	0.21	0.39	8.1	1.9	28	8.3
6356	−0.03±0.05	0.14	0.75	13.8	0.7	35	35
6440	0.06±0.06	0.18	0.18	6	30	≲48	≤ 3
6517	−0.01±0.04	0.12	0.26	8.8	19	35	1.7
6522 (U)	−0.17±0.24	0.75	1.1	7.3	12	28	1.4
6624	14.3 ±0.10†	...	15†	6	5	28	2.8
6681	−0.10±0.05	0.15	0.58	11.7	5.9	26	2.3
6712(U)	0.70±0.07†	...	1.0†	6.8	0.15	20	35
6715	−0.20±0.08	0.24	3.2	21.9	5.2	48	13
6760 (U)	−0.03±0.04	0.12	0.03	2.6	1.4	16	2.1
6779 (U)	0.07±0.03	0.16	0.53	10.8	0.07	18	54
MXB 1730−335	1.50±0.15‡	...	4.3‡	(10)	40	60	4
GCX	0.41±0.24	0.72	2.0	(10)	...	...	...
Norma	0.35±0.26	0.78	2.2	(10)	...	...	...

NOTE.—(U) indicates those clusters with *Uhuru* upper limits (Ulmer *et al.* 1976). With additional *Uhuru data*, NGC 6712 was later detected by Cominsky *et al.* (1977).

* Derived from Peterson 1976 or Peterson and King 1975 except for NGC 6440 (Bahcall and Hausman 1976) and MXB 1730−335 (Kleinmann *et al.* 1976).

† Detected emission.

‡ Averaged emission during bursts.

sources, the peak "steady" emission luminosities observed are a factor of $\gtrsim$10–30 above our upper limits. The large range of d.c. flux variability for these proposed globular cluster sources has not been reported for the sources associated with NGC 6441, NGC 6624, and NGC 7078, which have the smallest position uncertainties. Certainly better source positions are needed to establish whether the more transient-like sources near NGC 1851 (MX 0513−40) and NGC 6440 (MX 1746−20) are also in fact in the cores of these globular clusters. Assuming the cluster identifications are valid for these, however, it is clear that the large range of X-ray luminosities possible means that upper limits such as in Table 1 may be time-dependent as well as subject to the uncertainties in cluster distances. At least another order of magnitude in sensitivity (available with HEAO) or else fortuitous observations are required to establish additional possible cluster sources if their steady emission is as variable as that of MX 0513−40 and MX 1746−20.

III. OBSERVATIONS OF A1850−08 (=NGC 6712?)

The source A1850−08 near NGC 6712 (Seward *et al.* 1976; Cominsky *et al.* 1977) was detected by both the SXX and HXX detectors on ANS during observations from 1976 April, 2.12 to 5.24. The mean flux level of 0.70 ct s^{-1} was comparable to that observed by *Ariel 5* (Seward *et al.* 1976). Significant flux variations were observed over time scales of at least two orbits ($\gtrsim$3 hours): a factor of ~2 increase in flux was observed by HXX for two orbits around April 3.00, whereas the source was not detectable ($>2\sigma$ below mean flux) for two orbits around April 4.80. No eclipses (~$0^d.5$–2^d) or periodicities (>50% of flux) were seen, although variations by at least a factor 2 were observed; however, the limited statistics and observation coverage restricted this search.

An improved line of position for this source was obtained from the ratio of counts in the two HXX detectors. The observed ratio of 0.58 ± 0.30 yields a most probable source position of 4′ ± 3′ (90% confidence level) south of the pointing position, which was the center of NGC 6712 as given by Arp (1965). This band of position is shown in Figure 1 along with the *Ariel 5* (Seward *et al.* 1976) and *Uhuru* (Cominsky *et al.* 1976) positions. In the perpendicular (≈R.A.) direction, the ANS position is restricted to be within ~ ±0°.6 of NGC 6712, by the ratio of SXX/HXX apparent flux. We have combined the 90% error boxes from *Ariel 5* and *Uhuru* with the ANS result for a combined 90% confidence error box by calculating the appropriate two-dimensional Gaussian contours. The result is also shown in Figure 1: although the most probable source location is ~4′ SE of NGC 6712, the cluster core can not be excluded. Since the combined error box is ~0.015 square degrees, the probability (Clark *et al.* 1975) of chance association with NGC 6712 is apparently only ~10^{-4}. The actual probability may be somewhat greater though, if there are significant numbers of obscured clusters near the galactic plane.

It is also noteworthy that the new error box contains several irregular variable stars outside the globular cluster (Sandage, Smith, and Norton 1966; Rosino 1966). One of these (V15) is indicated in Figure 1. This star is interesting in that it displays "slow irregular fluctuations of relatively small amplitude as well as fast

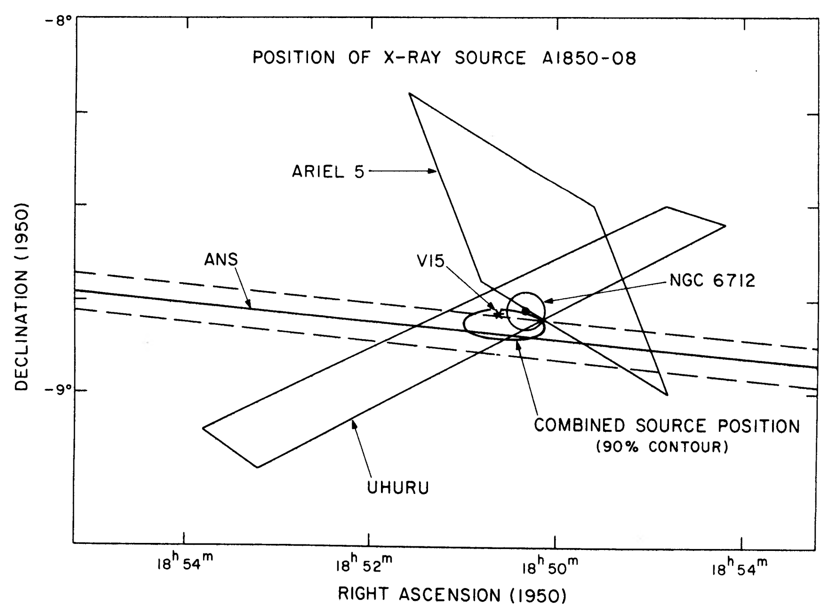

FIG. 1.—ANS position band (90% confidence) for A1850−08. Also shown are the error boxes from *Ariel 5* and *Uhuru* and the combined (90% confidence level) source location contour. The globular cluster NGC 6712 is shown with a 6′ diameter (Rosino 1966); the cluster core ($\lesssim$1′) is at the edge of the new box. The rich field includes several variable stars such as V15 that are outside the cluster but in the error box and worthy of further study as candidates for the source identification.

fluctuations in the course of a night" (Rosino 1966), which is similar to the typical X-ray variation time scales. Thus, depending on the space density of such stars, the probability of its chance inclusion in the error box may also be small. Until a better X-ray position is available, this variable is a good candidate, and clearly this and other variables in the box are worthy of further study (upon examining HCO archived data, M. Liller [1976] has found that this star shows rapid fluctuations and a possible long period). Since the source A1850−08 is in the Scutum Cloud, one of the highest surface brightness regions of the Milky Way, optical identification of the source outside the cluster may be nearly as difficult as if it is in fact in the cluster core.

Until a better X-ray position can positively confirm the cluster identification (and possible offset from the core), the source spectrum may offer additional clues. The combined SXX–HXX spectra for power law fits yield an energy index $\alpha = 0.6$ (+0.6, −0.5) and absorption column density $n_H < 3 \times 10^{22}$ cm^{-2}, and for exponential fits $kT = 7$ (+?,-3) keV and $n_H < 2 \times 10^{22}$ cm^{-2}. During the factor of ~2 flux increase on April 3, we found $kT \geq 9$ keV and $n_H < 5 \times 10^{22}$ cm^{-2}. These column density limits are consistent with the source being at least at the ~6.8 kpc distance of NGC 6712 (for which $A_V \approx 1.5$ suggests $n_H \approx 3.3 \times 10^{21}$ cm^{-2} [Gorenstein 1975]), though there can of course be substantial low-energy absorption in the source. For comparison, during the factor of ~40 increase flare observed by *Uhuru* (Cominsky *et al.* 1977), the absorption was less than 4×10^{22} cm^{-2} for a best-fit exponential spectrum with $kT = 4.5 \pm 1$ keV. The fact that our best-fit spectra are marginally harder than this suggests that the excess emission in the *Uhuru* flare is relatively soft. There is also evidence that our steady emission spectrum for A1850−08 is harder than that observed by ANS for the globular cluster NGC 6624 (or 3U1820 −30), which has a similar low-energy cutoff (Grindlay *et al.* 1976). The "hardness ratio" of source counts detected by HXX in the energy range 3.63–11.31 keV versus 1.84–3.63 keV is 1.84 ± 0.64 for A1850−08 and 1.26 ± 0.05 for 3U1820−30. Thus there is a suggestion that the steady emission from A1850−08 may be harder than the known globular cluster sources (except for MX0513−40 = NGC1851, which may also be hard [Clark *et al.* 1975]) though probably still softer than the galactic binary ssurces, which typically yield (Jones 1976) $kT \geq 10$ keV.

IV. CONCLUSIONS

The upper limits obtained for steady emission from some cluster sources (e.g., NGC 6440 and NGC 1851) requires that conditions producing the medium energy (~1–10 keV) X-rays in these objects must be variable by factors of greater than 10 over time scales of longer than days. Presumably these are either changes in average accretion rate or changes in optical depth (and medium energy X-ray production) or both. Our results (Table 1) limit the low-energy luminosity of both compact and diffuse globular clusters to be usually less than 3×10^{35} ergs s^{-1}. When detectable, the cluster sources are usually well above this threshold by a factor of $\gtrsim 3$. Typical globular cluster luminosities are $L_x \sim 3 \times 10^{36}$ ergs s^{-1} and are thus *not* among the most luminous of the galactic sources of medium-energy X-rays.

Our observations lead us to conclude that it is most probable that A1850−08 is associated with the diffuse globular cluster NGC 6712 but with a source location possibly outside the cluster core. Given the crowded field and known irregular variables, nonassociation with the cluster also remains a strong possibility. In either case, the relatively hard steady source spectrum provides marginal evidence that this source may be different from the sources known to be in the cores of centrally condensed globular clusters (e.g., NGC 6624 and NGC 7078).

On the other hand, if an X-ray position with less than 1′ uncertainty shows that the source is in fact in the cluster core, it will be significant for cluster source models. The low stellar density in the core (cf. Table 1) decreases the probability for binary formation (Hills 1975) whereas the escape velocity is still high enough to capture a significant amount of cluster gas onto a central massive black hole. In this case, the diffuse appearance of NGC 6712 (versus the condensed X-ray clusters) could indicate that the cluster has been partially disrupted and was formerly of high central density (Grindlay 1977*b*). In the extreme case, such a cluster would leave behind only a "core remnant" which, upon passing through interstellar clouds, could account for many of the X-ray burst sources (Grindlay 1977*a*). It is even possible that A1850−08 or NGC 6712 is also a burst source since Swank *eta l.* (1976); have reported an X-ray burst from a ~3° region containing the cluster. Further optical studies (e.g., velocity dispersons) and higher-sensitivity searches for X-ray emission (steady or bursts) from both diffuse and condensed globular clusters are urgently needed.

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