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OBSERVATIONS OF VARIABLE X-RAY SOURCES IN GLOBULAR CLUSTERS*

GEORGE W. CLARK, THOMAS H. MARKERT, AND FUK KWOK LI
Physics Department and Center for Space Research, Massachusetts Institute of Technology
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ABSTRACT

Observations with the MIT detectors on the OSO-7 satellite have revealed a previously unreported variable hard X-ray source at midgalactic latitude in the globular cluster NGC 1851. The source, designated MX 0513−40, varied in intensity by a factor $\gtrsim 5$ in 16 days and had a peak 12-day average energy flux of 4.7×10^{-10} ergs cm^{-2} s^{-1} in the energy range 1–10 keV, with $dN/dE \sim E^{-1.4}$. Observations of the X-ray sources 3U 2131+11 and 3U 1746−37 are also reported which confirm their locations in globular clusters NGC 7078 (M15) and NGC 6441, respectively, and demonstrate that they too are variable.

Subject headings: globular clusters — X-ray sources

I. INTRODUCTION

The third *Uhuru* catalogue (Giacconi *et al.* 1974) lists three sources with error boxes that contain globular clusters: two, NGC 6441 and 6624, at low latitude within 10° of the galactic center, and the third, NGC 7078 (M15), at $b^{II} = +28°$. The source associated with NGC 6624 was observed to be bright (250 counts s^{-1}) and variable. The other two were fainter and reportedly steady.

We report here the discovery of a new and particularly interesting occurrence of this phenomenon, viz, a variable X-ray source at midgalactic latitude in the globular cluster NGC 1851. We also report new observations which confirm the existence of X-ray sources in NGC 7078 (M15) and NGC 6441 and demonstrate that they are both variable. A search of the region around M92 revealed no X-ray source.

II. OBSERVATIONS

We made our observation with the MIT detectors on the OSO-7 satellite. The instrumentation has been described previously by Clark *et al.* (1973). The present results are based on data obtained from the Ne (1–6 keV) and Ar (3–10 keV) proportional gas counters behind both the 1° and the 3° FWHM tubular collimators.

a) MX 0513–NGC 1851

The new source was first detected in one of the cumulative sky maps in which we superpose data from successive 8-day periods of observation. The source is not apparent in other cumulative maps covering the same region. We determined the position and the average intensity of the source during the period when it was clearly visible by a maximum-likelihood analysis of the data from both the Ne and Ar counters. The result for the position was $\alpha = 5^h13^m.4 \pm 0^m.7$, $\delta = -40°6' \pm 8'$ (1950.0), where the indicated errors are standard deviations. The corresponding galactic coordinates are $l^{II} = 244°.5$ and $b^{II} = -34°.9$. The area of the 90 percent error circle is 0.18 deg^2. Keeping with the general convention of the *Uhuru* catalog, while at the same time distinguishing X-ray sources discovered in this MIT survey, we designate the new source MX 0513−40.

With the position fixed at the above location, we determined the maximum-likelihood values or the upper limits of the average intensities during other periods when the region was scanned. Figure 1 is a graphical summary of the intensity measurements in the 3–10 keV energy range versus time. The maximum value was a 12-day average of $(4.7 \pm 0.5) \times 10^{-10}$ ergs cm^{-2} s^{-1} in the energy interval from 1 to 10 keV. A 5-day mean centered 16 days earlier gives an upper limit of 1.0×10^{-10}. The source is too weak to permit a useful analysis of time variations during any one scan.

The spectral hardness in the 1–10 keV energy range can be characterized by the ratio of average intensities in the Ar and Ne detectors. During the period of maximum intensity, this ratio was 0.61, which is the ratio that would be produced by a power-law number spectrum $dN/dE \sim E^{-n}$ with $n = 1.4$. The corresponding values of the ratio and n for the Crab Nebula are 0.39 and 2.1, respectively. The spectrum of the new source is therefore hard compared with that of the Crab Nebula in the 1–10 keV range. The data are not sufficient to determine whether this is attributable to the effects of absorption.

The globular cluster NGC 1851 lies within the 90 percent error circle of MX 0513−40. No other NGC object nor any radio source in the Sydney (MSH) survey lies within 2°.

b) 3U 2131—M15

We analyzed our data for the region around the globular cluster NGC 7078 (M15) and found a source with a 90 percent error circle of area 0.18 deg^2 which overlaps the cluster as shown in Figure 2 along with the *Uhuru* error box for the X-ray source 3U 2131+11. We

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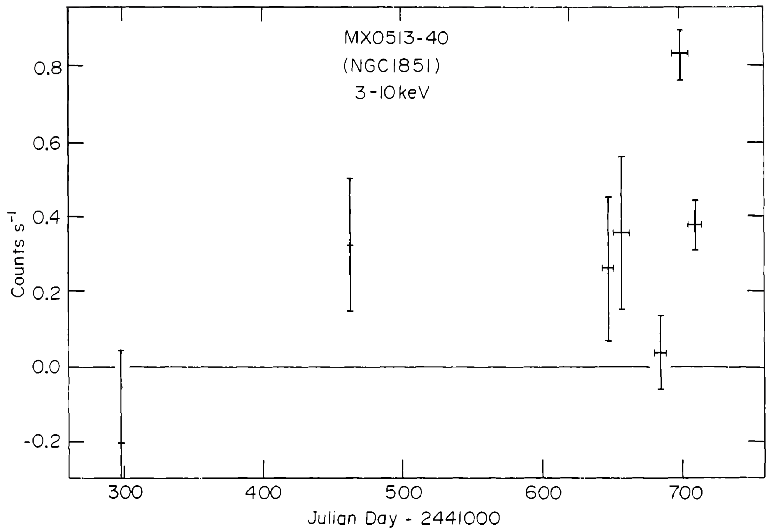

FIG. 1.—Plot of X-ray intensity versus time for MX 0513 − 40

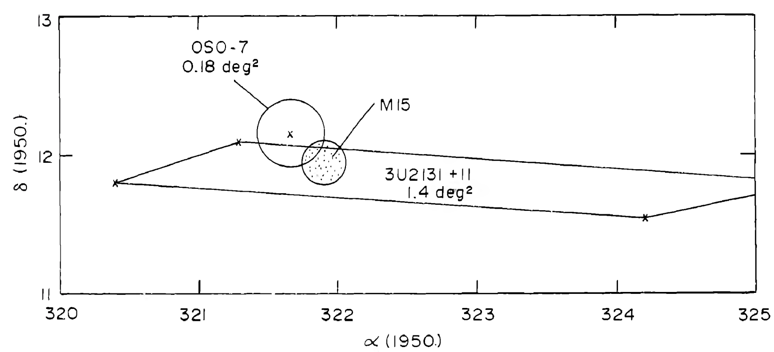

FIG. 2.—Position determinations of the source associated with NGC 7078 (M15) from *Uhuru* and OSO-7 data

measured the average intensity of the source during three separate sightings and found that it varied by more than a factor of 2 over 500 days as shown in Figure 3.

c) 3U 1746–NGC 6441

The X-ray source 3U 1746−37 lies in a crowded region near the galactic center. In order to avoid source confusion in our examination of this source, we used only the data obtained with the 1° FWHM detectors which afford, on the average, a ninefold lesser exposure than the 3° FWHM detector on any given object. Nevertheless, the data obtained during several separate scans demonstrate the existence of a source at a position with a 90 percent error circle that includes the globular cluster. This uncertainty area, however, is substantially larger than that of the *Uhuru* error box which also encloses the cluster, so that little additional weight is added to the identification suggested in the 3U catalog. On the other hand, our data do give strong

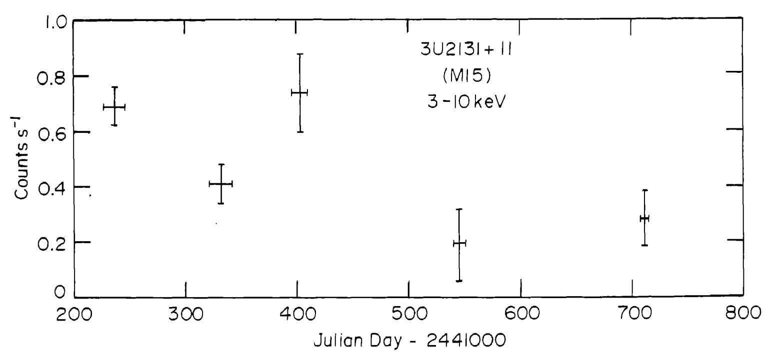

FIG. 3.—Plot of X-ray intensity versus time for the M15 source

evidence of variability as shown by the intensity data summarized in Figure 4.

d) M92

We examined our data for evidence of X-ray emission from M92, suggested in the 3U catalog (Giacconi *et al.* 1974) as the counterpart of the weak and poorly positioned source 3U 1736+43. We found no evidence of an X-ray source at the position of M92 in two separate scans over the region, and we place an upper limit of 0.6×10^{-10} ergs cm^{-2} s^{-1} on its luminosity in the 3–10 keV energy range.

III. DISCUSSION

Table 1 summarizes the data on the four variable X-ray sources and the globular clusters with which they appear to be associated.

The probability that the position of a globular cluster may lie by accident within the error area of an unrelated X-ray source is the product of the error area times the local density of globular clusters. The clusters form a nearly spherical halo around the center of the galaxy. To sufficient accuracy, their density in the sky can be described as a function of the spherical angle, θ, between a given direction and the direction of the galactic center by the formula

$$dN/d\Omega = 9.45 \times 10^{-2} \exp\,[40(\cos\theta - 1)] + 6.40 \times 10^{-3} \exp\,[1.83(\cos\theta - 1)] \text{ clusters deg}^{-2}\,,$$

which integrates to the total of 119 known clusters over the entire sphere and which we have fitted to the distribution $N(>\theta)$ of the known clusters (Arp 1965). The probability of a chance coincidence for each of the sources was computed with this density formula and is listed in Table 1. In all four cases the probability is much less than 1 percent.

Another statistic of interest in an evaluation of the significance of the apparent source-cluster relation is the expected total number of accidental coincidences between globular clusters and the error areas of all known X-ray sources. To find this, we multiplied the error areas of each of the sources listed in the *Uhuru* catalog (Giacconi *et al.* 1974) by the density of globular clusters at the source position according to the above formula, and then summed the products. Taking all the 3U sources with error boxes of area less than 6 deg^2, we found that the expected number is 0.13. It follows that

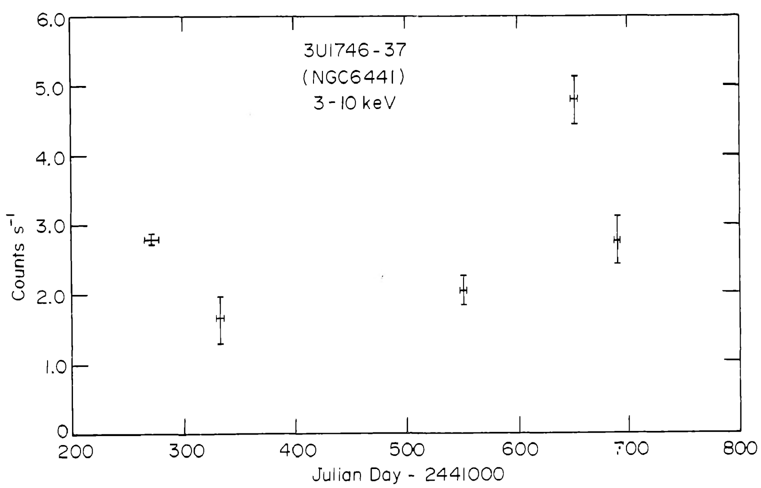

FIG. 4.—Plot of X-ray intensity versus time for the source associated with NGC 6441

TABLE 1

SUMMARY OF DATA ON X-RAY SOURCES AND THE GLOBULAR CLUSTERS IN WHICH THEY APPEAR TO BE LOCATED

X-Ray Source				Globular Cluster*						Probability of Accidental Coincidence	
Name	b^{II} l^{II} (deg)	90% Conf. Area (deg^2)	1–10 keV Energy Flux (var) (10^{-10} ergs cm^{-2} s^{-1})	Name	Conc. Class	Diameter (arcmin)	Sp	Distance (kpc)	Rad. Vel. (km s^{-1})	($\times 10^{-4}$)	L_x (10^{36} ergs s^{-1})
MX 0513−40	−34.9, 244.5	0.18	4.7(≥5)	NGC 1851	II	11	F7	9.5	+309	1.0	4.7
3U 1746−37	− 5.0, 353.6	0.0184†	20.(2)	NGC 6441	III	. . .	G2	(10)	−70	12.9	23.
3U 1820−30	− 7.9, 2.8	0.0006†	88.(5)	NGC 6624	VI	4.2	G5	(10)	+69	0.42	100.
3U 2131+11	−28.1, 65.6	0.18	3.0(2)	NGC 7078, M15	IV	9.4	F2	10.5	−107	3.7	3.7

* Data from Arp 1965. † *Uhuru* data from Giacconi *et al.* 1974.

the probability of having four accidental coincidences in these error boxes is less than 10^{-6}, which is so small as to make nearly certain the identification of the X-ray sources as members of the clusters which lie in their respective error areas.

Additional evidence of cluster membership in the case of two midgalactic latitude sources is provided by their variability which is a universal property of all identified stellar X-ray sources, but rare among X-ray sources at latitudes $|b^{II}| > 10°$ which are presumably mostly extragalactic suprastellar objects. Indeed, the only previously known variable sources in the region $|b^{II}| > 10°$ are the identified stellar objects Cyg X-2, Sco X-1, Her X-1, and SMC X-1, and the as yet unidentified but presumably stellar objects in the Large Magellanic Cloud, for which evidence of variability was recently reported by Rapley and Tuohy (1974) and Markert and Clark (1975). It seems very likely, therefore, that both MX 0513−40 and 3U 2131+11 are stellar objects, and that their absolute luminosities are less than 10^{39} ergs s^{-1}, the approximate upper limit of the luminosity function of galactic sources (Seward *et al.* 1972). Given their measured intensities, the sources cannot be more distant than ~160 kpc, which is adequate to allow membership in a globular cluster but not in any more distant aggregate of stars that may exist close to the measured lines of sight.

NGC 1851 was, until recently, a neglected southern-sky object described in the Dreyer catalog as a remarkable globular cluster, very bright, very large, round, well resolved, and extremely bright at its center. Its compactness is class II, and it has the typical attributes of globular clusters in the outer galactic halo—namely, an early-type composite spectrum (F7) and a high radial velocity (+309 km s^{-1}). Recently, Alcaino (1971) determined its distance to be 9.5 kpc on the basis of the apparent magnitude of its horizontal branch and an estimate of reddening obtained by fitting its giant sequence to the giant sequence of better-measured clusters of comparable metallicity. At that distance the maximum observed luminosity of the X-ray source would be $\sim 5 \times 10^{36}$ ergs s^{-1}.

The distances of the two low-latitude clusters have not been determined, but their nearness to the galactic center makes it reasonable to assume distances of 10 kpc for both. At this distance, the X-ray luminosity of 3U 1746−37 is 2.1×10^{37} ergs s^{-1}. Canizares and Neighbours (1975) have recently studied 3U 1820−30 with the OSO-7 data and have confirmed its identification and variability. Their value for the luminosity at 10 kpc is 1.0×10^{38} $ergs^{-1}$ s^{-1}.

Prior to the discovery of X-ray sources in globular clusters there was no direct evidence for the existence of gravitationally collapsed stellar remnants in these pure assemblages of ancient, extreme Population II stars. White dwarfs have absolute magnitude $M_v > 10$, so that they cannot be observed at the distances of globular clusters of which the least distance modulus is ~13. On the other hand, Sandage (1957) showed in the case of M3 that the difference between estimates of the dynamical mass and of the mass of the observed stars was consistent with, but not accurate enough to prove, the assumption that ~30 percent of the total mass is in invisible exhausted stars which at that time he supposed were all white dwarfs. Several stars of types generally thought to be close binaries undergoing mass exchange with white dwarf components have been observed in globular clusters, namely, three novae and two U Geminorum variables (Kukarkin and Mironov 1971). Peebles (1972) has discussed the effect of a massive black hole on the spatial distribution of the stars in a cluster and has derived an expression for the distribution of light intensity over the affected region of the cluster. No observational evidence of such an effect has been reported.

Now, with the discovery of variable cluster X-ray sources, we have strong evidence for the existence in globular clusters of binaries with neutron stars or black holes. This raises a number of interesting questions, not only as to why the frequency of occurrence of X-ray sources among the stars in globular clusters is ~100 times greater than among the stars of the whole Galaxy, but also as to how they come to exist at all under the conditions peculiar to the globular clusters. It is suggested elsewhere (Clark 1975) that these sources are capture binaries formed from the ancient remnants of single massive stars, and it is predicted that refined position measurements will show that the sources lie near the centers of the clusters.

We note with interest the discovery by Vidal and Freeman (1975) of an ultraviolet-bright star within the error box of MX 0513−40 and 0'.5 from the center of NGC 1851.

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George W. Clark, Fuk Kwok Li, and Thomas H. Markert: Center for Space Research, MIT, Cambridge, MA 02139