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RADIO AND X-RAY OBSERVATIONS OF NGC 1851 AND NGC 1904

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ABSTRACT

Radio and X-ray observations of the globular clusters NGC 1851 and NGC 1904 were conducted in 1975 December. A number of weak radio sources have been detected in the field of each cluster at 2695 and 8085 MHz. No single dominant sources were found which could be identified with the cores of these clusters. X-ray observations of NGC 1851 indicate a steady X-ray source having an intensity of $(1.0 \pm 0.1) \times 10^{-10}$ ergs cm^{-2} s^{-1} in the 3–9 keV range, and a 2 σ upper limit of 5×10^{-11} ergs cm^{-2} s^{-1} has been obtained for X-ray emission from NGC 1904. No evidence for time variation was found in either the radio or X-ray signals.

Subject headings: clusters: globular — radio sources: general — X-rays: sources

I. INTRODUCTION

X-ray sources in the vicinity of five globular clusters have been reported recently by Giacconi *et al.* (1974), Clark, Markert, and Li (1975), and Markert *et al.* (1975). Evidence for associating these sources with the globular clusters is given by Clark, Markert, and Li (1975), who also present data indicating the X-ray emission varies by factors of 2–5. These X-ray sources are especially interesting, since they may differ from other galactic sources powered by mass accretion either in their evolution or in the character of the compact object and the accretion process. Clark (1975), Fabian, Pringle, and Rees (1975), and Sutantyo (1975) have proposed that these globular cluster sources are X-ray binaries formed by a normal star capturing a compact object rather than by evolution of a primordial binary system. Alternatively, Bahcall and Ostriker (1975) and Silk and Arons (1975) have suggested the X-ray emission arises from a massive central black hole accreting ambient cluster gas.

We report here results of observing two globular clusters, NGC 1851 and NGC 1904, simultaneously at radio and X-ray wavelengths using the NRAO Green Bank interferometer[1] and the UCL collimated proportional counter on the OAO *Copernicus* satellite. One of us (Johnson 1976) has also surveyed nine other globular clusters using the NRAO interferometer and has found one or more radio sources within the field of each cluster.

The location of an X-ray source, MX 0513−40, has been determined by Clark, Markert, and Li (1975) to be about 11′ east of NGC 1851 with a 1 σ error radius of 8′. The core and tidal radii of NGC 1851 are 8″ and 22′, respectively (Peterson and King 1975), so the X-ray source is well within the projected area of the orbits of stars in the cluster. Clark, Markert, and Li (1975) also report the intensity of this source in the 3–10 keV band has varied by a factor $\geqslant 5$ in 16 days and have found it to be below detectability on two occasions. Very recently, Jones and Forman (1976) have reported an X-ray source in a region of the sky centered on NGC 1851 which varied by a factor $\geqslant 25$ in a time of less than 5 minutes. If associated with MX 0513−40, this variability is on a time scale comparable to that observed for NGC 6624 by Grindlay *et al.* (1976). By analogy with other well-known binary X-ray sources, Vidal and Freeman (1975) proposed the identification of MX 0513−40 with a B6 III star showing Hβ in variable emission, which they discovered about 0′.4 southeast of the center of NGC 1851.

NGC 1904 is a cluster of core and tidal radii, respectively, equal to 16″ and 11′ (Peterson and King 1975). Although not one of the known X-ray sources, NGC 1904 was observed because it is a large globular cluster and exhibits dark clouds which support the possibility that stellar ejecta are retained as intracluster gas (Roberts 1960). Also, NGC 1904 was observed because emission from globular cluster sources is known to be highly variable and, for this reason, its X-ray emission might have escaped detection on previous observations.

II. RESULTS

Radio observations of NGC 1851 were conducted on 1975 December 7, 8, 10, and 11 for approximately 100 minutes on each night between ~0420 and 0630 UT. NGC 1904 was observed nightly on 1975 December 7–11 during periods between 0200 and 0900 UT for a total time of ~14 hours. X-ray observations on NGC 1851 were carried out on 1975 December

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

RADIOFREQUENCY OBSERVATIONS OF TWO GLOBULAR CLUSTERS

NGC	Total n	ν (MHz)	S_ν (mJy)	α(1950)	δ(1950)	$\alpha - \alpha_0$	$\delta - \delta_0$	P
1851.......	412	2695	3 ± 1.5	$05^h12^m21.4$	−40°00′38″	−30″	+262″	5×10^{-1}
	412	2695	2 ± 1.5	15.9	06 46	−93	−106	10^{-1}
	412	2695	4 ± 1.5	18.9	04 11	−58	+49	4×10^{-2}
	412	2695	4 ± 1.5	20.4	04 37	−41	+23	10^{-2}
	412	8085	6 ± 2.5	18.0	03 31	−69	+89	2×10^{-2}
	412	8085	6 ± 2.5	16.5	04 15	−86	+45	10^{-2}
	412	8085	6 ± 2.5	21.3	04 30	−31	+30	2×10^{-3}
	412	8085	6 ± 2.5	23.4	06 27	−7	−87	10^{-2}
1904.......	875	2695	3 ± 1.0	$05^h22^m15.4$	−24°29′43″	+46″	+257″	5×10^{-1}
	875	2695	3 ± 1.0	2.7	32 02	−127	+118	2×10^{-1}
	875	2695	3 ± 1.0	24.4	38 17	+169	−257	6×10^{-1}
	875	8085	5 ± 1.7	12.8	34 55	+11	−55	5×10^{-3}
	875	8085	5 ± 1.7	13.0	34 46	+13	−46	4×10^{-3}
	875	8085	5 ± 1.7	10.5	35 02	−20	−62	7×10^{-3}
	875	8085	5 ± 1.7	12.0	34 01	0	−1	2×10^{-6}

10 between 0452 and 1538 UT for a total of nearly 6 hours, and for ~6.3 hours on 1975 December 11 between 0318 and 1503 UT. NGC 1904 was observed by *Copernicus* for a period of 2.1 hours on 1975 December 9 between 0540 and 0940 UT. The combined radio and X-ray observations provided simultaneous coverage of each object for a total of ~1 hour.

The interferometer was used in the 2700–1800–900 m configuration and in the dual-frequency mode at 2695 MHz and 8085 MHz, following standard NRAO procedures. This includes interruptions of clusters scans for calibration data of amplitudes and phases, using calibrators which are near the clusters from the latest revision of the NRAO list and alternating integration periods with the interferometer between the two frequencies every 30 s.

Source size, coordinates, and flux density have been derived from the interferometer maps having fields of view 18′ × 18′ at 2695 MHz and 6′ × 6′ in 8085 MHz. Mapping combines all integrations in each frequency. Each map center α_0, δ_0 is identical with the epoch 1950 coordinates of the cluster center cataloged by Hogg (1963) within the map-cell size, 4″.2 square at 2695 MHz and 1″.4 square at 8085 MHz. From telescope data tapes the computer produces maps of the synthesized beam and sidelobe response to an ideal point source, as it would be observed with the same spacings and hour angles that are actually used for each sky map. The peak brightness temperature of a point source in each frequency is calibrated in mJy for the maps of sky sources according to the interspersed calibrator observations. The elliptical Gaussian beam dimensions at 2695 MHz are computed to be 27″ × 14″ at position angle 0° in NGC 1851, and 13″ × 1″.9 at position angle −6° in NGC 1904. These dimensions are about one-third as large at 8085 MHz. The interferometer is insensitive to sources which are appreciably larger than these beam dimensions, and a source of intermediate size will be unequally resolved at the two frequencies.

Inspection of the various maps indicates a series of diffraction patterns characteristic of a number of weak sources in the field of each cluster. Table 1 gives the data for those sources which are most certain. The total number of integrations in each frequency is n, and the estimated rms error of flux density S_ν is $\pm 30\, n^{-1/2}$ mJy at 2695 MHz and $\pm 50\, n^{-1/2}$ mJy at 8085 MHz. Identical values for the observed flux densities in several cases result from the discrete levels of the data reduction. The last column of Table 1 gives the probability p that a cosmic field source of flux density S(2695 MHz) falls within the distance $[(\alpha - \alpha_0)^2 + (\delta - \delta_0)^2]^{1/2}$ of the cluster center coordinates taken as α_0, δ_0. This is done by interpolating among empirical source counts N(2700 MHz) sr^{-1} plotted by Fomalont, Bridle, and Davis (1974). Similar data for N(8085 MHz) sr^{-1} are not available, but extrapolation of the results at lower frequencies suggests that N(8085 MHz) sr^{-1} ≈ 0.3 N(2700 MHz) sr^{-1}. Although individual sources are marginal in some cases and it is likely that some of those listed in Table 1 are cosmic field sources, their combined pattern in the primary maps of the two clusters is significant. For example, the probability of observing two cosmic field sources at 2695 MHz of intensity 4 mJy within a 75″ radius of the center of NGC 1851 is ~0.0016.

The reference coordinates α_0, δ_0 for the cluster centers are cataloged only to 0^m.1 in right ascension and 1′ in declination. Because of these approximate coordinates we are unable to determine whether any of the sources in Table 1 lies at the true center of a cluster, or coincide with Vidal and Freeman's (1975) B6 III star in NGC 1851.

Inspection of the individual amplitudes of the interferometer correlators as they are listed each 30 s throughout the observations reveals no significant time variations of the type obtained in X-rays by Jones and Forman (1976).

The proportional-counter system on *Copernicus* is collimated to 2°.5 × 3° FWHM in two dimensions (the asymmetry is due to a Sun baffle), provides for six-channel pulse-height analysis in the range 2.9–8.7 keV and has a time resolution of 86.5 s (=1 frame)

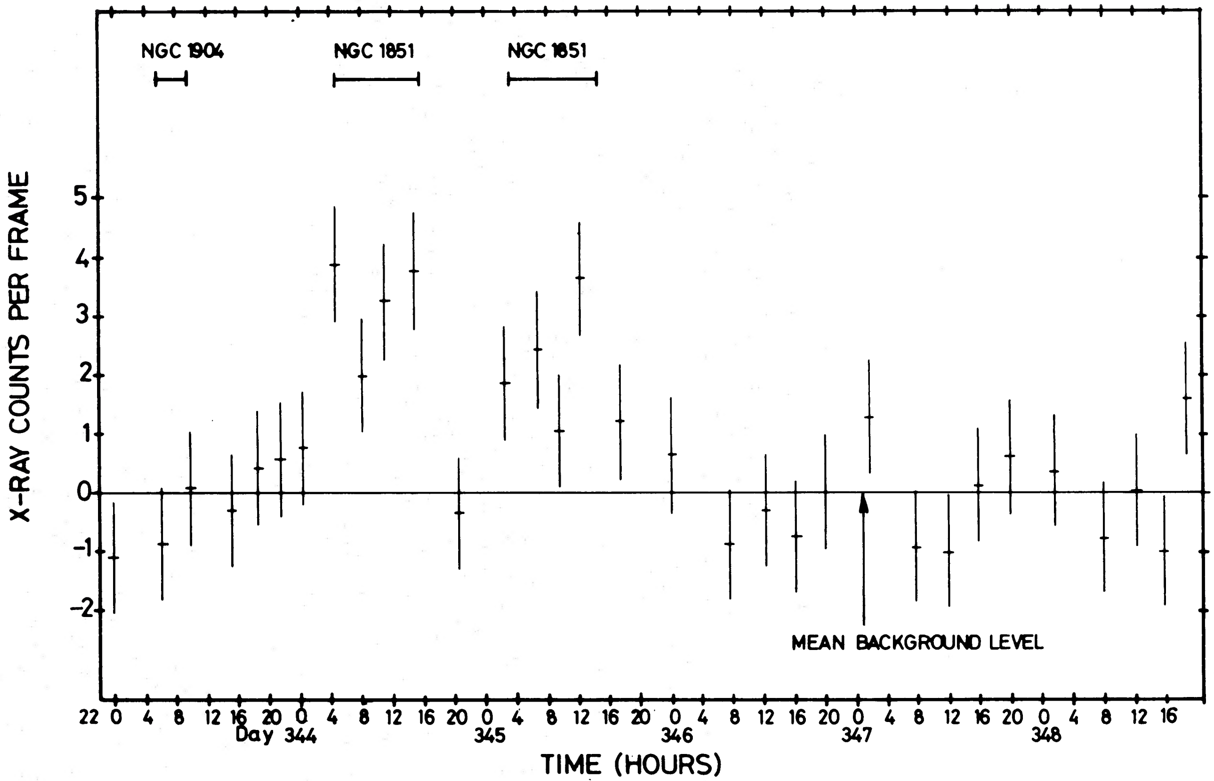

FIG. 1.—Counting rates in the UCL 3–9 keV detector during a five day interval in December 1975. Periods when NGC 1904 and NGC 1851 were observed are indicated. Background data were collected for other times when the field of view was pointed at non–X-ray sources during Princeton observations.

as used in the present observations. Details of this instrument and the methods used in conducting observations have been described previously by Sanford (1974) and Bowles *et al.* (1974). The data from several days of observations are plotted in Figure 1 (summed in 50 frame bins), including periods when the field of view was pointed at non–X-ray sources during Princeton observations. Background counting rates have been determined by the technique described by Davison (1974). The two observations of NGC 1851 clearly show an X-ray signal, while no significant increase in counting rate was found during the observation of NGC 1904.

When the entire data set from the *Copernicus* observations of the field of NGC 1851 is integrated, an X-ray signal eight standard deviations above background is obtained in the 3–9 keV range. The six-channel pulse-height data have been fitted both to a power law and to a function describing thermal bremsstrahlung. Because of statistical uncertainties, these data do not tightly constrain parameters of the fits and are consistent with a photon index $\sim -3 \pm 2$. However, in each case, the energy flux between 3 and 9 keV lies in the range $(1.0 \pm 0.1) \times 10^{-10}$ ergs cm^{-2} s^{-1}. This value indicates an X-ray intensity at the limit of detectability for the MIT observations (Clark, Markert, and Li 1975) and a factor of ~ 4 below the peak intensity they have observed for MX 0513$-$40. A detailed periodogram analysis (as described by White *et al.* 1976) yields an upper limit of 50% to variability of this source on time scales of 3–40 minutes.

The weak (2 *Uhuru* counts) source 3U 0510$-$44 has a very large positional uncertainty (18 square degrees) and, as such, it is possible that it could contribute (at the most extreme position) a *maximum* of 17% to the observed counting rate from the field of NGC 1851. However, at its most likely position *no* contribution is possible from this source. Another nearby source, 3U 0530$-$37, also lies outside the field of view of the X-ray collimator.

We have failed to detect an X-ray signal from NGC 1904 (see Fig. 1) and place a 2 σ upper limit of 5×10^{-11} ergs cm^{-2} s^{-1} on the flux from this object (assuming the same range of power-law indices as for NGC 1851).

III. DISCUSSION

None of the radio sources in Table 1 is confirmed in both frequencies at a common position. In three of the seven cases, 2695 MHz sources lie outside the 8085 MHz field of view and therefore could not be observed at the higher frequency. Also, some of the sources observed at 2695 MHz may be extended sufficiently so they are resolved at 8085 MHz and therefore are not detected at this frequency because of the resulting decrease in signal. However, all of the

8085 MHz sources should be detected at 2695 MHz unless the power-law spectral index is positive over the two frequencies. It should be noted that 8085 MHz sources without counterpart 2695 MHz sources are also observed in NGC 5024 and NGC 6205, and sources are observed in both frequencies in NGC 7078 and NGC 7089. These are the planetary nebula K648 with flat spectrum in NGC 7078, and a non-thermal source in NGC 7089. There is, additionally, a 2695 MHz source in NGC 7078, and only 2695 MHz sources in NGC 5272, NGC 5904, NGC 6440, NGC 6624, and NGC 6864 (Johnson 1976).

A positive radiofrequency spectral index has been found in several radio/optical objects; e.g., β Per and β Lyr (Wade and Hjellming 1972); MWC 349 and RY Sct (Hjellming, Blankenship, and Balick 1973); V 1016 Cyg (Seaquist and Gregory 1973); P Cyg (Wendker, Baars, and Altenhoff 1973); and T Tau and LkHα 101 (Spencer and Schwartz 1974). The positive spectral index is apparently well understood either as expected of a compact, "stellar" planetary nebula, as the spectrum of a star undergoing mass loss, or, equally well, as the spectrum of a collapsing protostar (Wright and Barlow 1975; Panagia and Felli 1975; Olnon 1975; Marsh 1975). Although Wright and Barlow specified "protostar," it is apparent that the process may apply to a variety of accreting masses, including those which produce X-radiation near a compact object. One of the above radio/optical objects with a positive spectral index, β Per, is also an X-ray source (Epstein 1975). Indeed, Davidsen and Ostriker (1974) first predicted a $+\frac{2}{3}$ spectral index for a model of Cyg X-3 in the limit $h\nu/KT \ll 1$. The highly variable nature of Cyg X-3 and the fluctuation of its radiofrequency spectral index between negative and positive values are well known (e.g., Hjellming and Balick 1972). Although another X-ray source, Cyg X-1, normally shows a very flat radio spectrum (i.e., of zero spectral index), the index can become positive as in the transient event of 1975 (Hjellming 1976). On the other hand, all members of the complex of radio sources at Sco X-1, including the variable central source, apparently remain nonthermal (Hjellming and Wade 1971). It appears then that there is a variety of radiofrequency spectral indices among sources with X-ray counterparts, and variable flux density is sometimes accompanied by variable spectral index. The weak and possibly variable radio sources in the field of globular clusters would probably require many more observations to understand them well.

It is not clear that any counterpart of the X-ray source associated with NGC 1851 has been detected in our radio observations, since we have observed no concurrent time variability which would have linked the X-ray and radio signals. However, it is possible to conclude that no single radio feature dominates the field of these globular clusters in the manner of which a very bright optical cusp dominates the center of some clusters (King 1975; Bahcall 1976; Fay *et al.* 1976). Further observations are required to determine whether known types of radio objects—for example, planetary nebulae—prevail in the fields of these globular clusters and in other clusters including NGC 6440, NGC 6624, and NGC 7078, which are also associated with X-ray sources.

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