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THE RADIO MORPHOLOGY OF THE X-RAY/RADIO SOURCES NEAR 0454+844 AND 1803+784

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ABSTRACT

The radio emission from the X-ray/radio sources within 20′ of the BL Lacertae sources 0454+844 and 1803+784 has been measured at 49, 20, 6, 2.8, and 2 cm. The radio spectral indices of the radio emission indicate that it is nonthermal in origin. The radio/X-ray source (0450+844) near 0454+844 has a size and spectral index that can be interpreted as emanating from an optically identified background galaxy and thus is probably not physically associated with 0454+844. The radio emission near 1803+784 is very complex and consists of at least four sources (1804+786, 1805+786, 1807+787a, and 1807+787b) that have steep spectral indices. These four sources appear to be spatially aligned with 1803+784. The possibility of this emission being physically associated with 1803+784 source cannot be ruled out. However, deep CCD investigations of the field near the bright radio sources 1807+787a, b indicate that the radio emission may arise from members of a background cluster of galaxies of which the compact radio source 1803+784 may or may not be a member.

Subject headings: BL Lacertae objects — galaxies: clustering — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

Six of the strongest sources of the MPIfR 5 GHz S5 survey contain compact radio cores that emit strongly at X-ray wavelengths (Biermann *et al.* 1981). X-ray emission has also been detected within 20′ of five of these sources and appears to be associated with the compact sources since the probability of serendipitous discovery at the observed flux density levels is low (Biermann *et al.* 1982). Three of these X-ray emission regions, 0454+844 (no. 3) and 1803+784 (nos. 1 and 3), have also been detected at cm wavelengths and appear to have nonthermal spectra (Biermann *et al.* 1982).

In order to investigate the nature of the radio/X-ray emission near the BL Lac objects 0454+844 and 1803+784 and their possible relationship with the compact radio/X-ray sources, we undertook further observations of them at 49, 20, 6, 2.8, and 2 cm.

II. OBSERVATIONS

The observations at 20, 6, and 2 cm were obtained using the D configuration of the Very Large Array of the National Radio Astronomy Observatory.[5] Twenty-seven antennas were used during a period of 7 hours on September 19, and 1 hour on 1981 September 20 at frequencies of 1465, 4885, and 15015 MHz with a bandwidth of 50 MHz. Typically the position of the radio/X-ray source was observed for 20 minutes followed by a 4 minute observation of the nearby compact radio source at each frequency. This sequence was cycled through 4 times for each source. In order to establish the flux density scale, 1328+307 was observed at the three frequencies and was assumed to have a flux density of 14.51, 7.41, and 3.41 Jy at 1465, 4885, and 15015 MHz, respectively (Baars *et al.* 1977). The flux densities and positions of the compact sources 0454+844 and 1803+784 are listed in Table 1.

The amplitude and phase of the compact radio sources 0454+844 and 1803+784 were used to calibrate the interferometer gain and phase of the observations of the radio/X-ray sources using the standard VLA software. The field centers were (1) $\alpha(1950) = 04^h50^m22\overset{s}{.}400$, $\delta(1950) = 84°25'04\overset{''}{.}0$, and (2) $\alpha(1950) = 18^h07^m58\overset{s}{.}8$, $\delta(1950) = +78°45'03\overset{''}{.}0$. Maps were made and cleaned using the CLEAN algorithm (Högbom 1974).

In addition to the VLA measurements, observations were made with the Effelsberg telescope and the Westerbork Synthesis Radio Telescope[6] (WSRT). The WRST telescope was used at 608.5 MHz with a 2.5 MHz bandwidth to observe the fields of both compact sources. The observations were carried out on 1981 June 21 for 0454+844 and on 1981 June 23 for 1803+784 in the standard synthesis mode (Högbom and Brouw 1974) with a shortest spacing of 72 m, an increment of 72 m, and a longest spacing of 2736 m and 1440 m for the two sources, respectively. Because of scheduling difficulties the hour angle coverage was −18° to +82° and +14° to +90°, corresponding to observation lengths of 6^h40^m and 5^h03^m. Calibration was achieved by observing 3C 147 before each measurement, assuming its flux density to be 37.78 Jy. The CLEAN algorithm (Högbom 1974; Schwartz 1978) was used to produce the final maps. The Effelsberg

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TABLE 1

Radio Emission Near the X-Ray Lobes in the Fields of 0454+844 and 1803+784

Source	α(1950)	δ(1950)	49 cm (mJy)	20 cm (mJy)	6 cm (mJy)	2 cm (mJy)	Comments
0450+844	$04^h50^m22^s.280$	+84°25′05″.9	45	29	28	12	X-ray component no. 3; radio size less than 10″; 17–18 mag galaxy
0454+844	04 54 57.153	+84 27 53.0	370	670	970	680	Compact S5 source; BL Lac object
1803+784	18 03 39.177	+78 27 54.3	1745	2850	2060	2370	Compact S5 source; BL Lac object
1804+786	18 04 40.97	+78 38 38	25	14	...	...	R-4
1805+786	18 05 49.084	+78 41 33.2	50	29	2	...	R-3
1807+787a	18 07 28.38	+78 43 24	45	10	2	...	R-2
1807+787b	18 07 58.629	+78 44 55.9	160	72	21	8	R-1 a, b resolved into two components at 6 and 2 cm; X-ray component no. 1; three faint >22 mag objects (*R* filter)

telescope was used extensively (1981 July and August and 1982 January) at 10.7 GHz to map 7′ × 7′ fields around the X-ray/radio sources in the fields of 0454+844 and 1803+784. Other than the known sources (Biermann *et al.* 1982), no source was detected with an upper limit to the flux density of an undetected source of 15 mJy (3 σ).

III. RESULTS

The radio flux density of 0450+844 (0454+844 No. 3 Biermann *et al.* 1982) for 608.5, 1465, 4885, and 15015 MHz is listed in Table 1 along with its position. The position is accurate to 1″ in both coordinates. The flux densities are accurate to 10%. The VLA flux densities have not been corrected for attenuation by the primary beam pattern. The synthesized beams were 48″ × 21″ p.a. 147°; 79″ × 47″ p.a. −82°; 23″ × 15″ p.a. −73°; and 7″.9 × 4″.7 p.a. −77° at 608.5, 1465, 4885, and 15015 MHz, respectively. The size of the source is ≤10″. Thus it appears that this source has a nonthermal spectral index ($\sim$0.4, $S \sim \nu^{-\alpha}$) between 49 and 2 cm. The total flux densities at 5 GHz and those extrapolated to 15 GHz agree very well with those reported by Biermann *et al.* (1982). Thus it appears that we have accounted for all of the radio flux density as measured by the Effelsberg telescope between 5 and 15 GHz. The spectra of 0454+844 and 0450+844 are displayed in Figure 1*a*.

A 17–18 mag galaxy has been found within 0″.4 of the above position at $\alpha(1950) = 04^h50^m22^s.48$; $\delta(1950) = +84°25′05″.6$. This object is very red on the POSS. It appears to be "fuzzy" leaving no doubt that it is extended. Within 1′ of the position of the X-ray/radio source there are three more red, extended objects which are all fainter than 18 mag.

Maps of the radio emission near 1803+784 are shown in Figures 2, 3, and 4. Figure 2 displays the 49 cm map. There are at least five components identified. Figure 3 displays the 20 cm map and shows at least four components. The radio sources are denoted by R1 through R5 (see Table 1 for IAU source designation) while + marks the positions of X-ray sources denoted by X-1 through X-4 (Biermann *et al.* 1982). Only 1807+787a, b (X-1) and 1803+786 (X-4) which is the BL Lac object, appear to be associated with radio emission. 1807+787b breaks up into two components at 6 cm as is easily seen from Figure 4. The flux densities at the four wavelengths are given in Table 1. It is evident that radio components 1807+787a and 1807+787b are not exactly aligned with the BL Lacertae object, 1803+784. The spectral indices (see Fig. 1*b*) of all these components appear to be quite steep. The synthesized beamwidths measured at 49, 20, 6, and 2 cm were 101″ × 38″ p.a. 127°, 85″ × 47″ p.a. 88°, 25″ × 14″ p.a. −88°, and 8″.3 × 4″.9 p.a. 85°, respectively. The positions of the components are listed in Table 1 and are accurate to 2″ in both coordinates. Since these components are resolved, the positions of peak flux density will not be the same at other frequencies or spatial resolutions. The positions listed in Table 1 of components 2–4 were measured at 20 cm, with the exception of 1807+787b which was measured at 6 cm. The flux densities are accurate to 10%. The sum of the flux densities for 1807+787a and

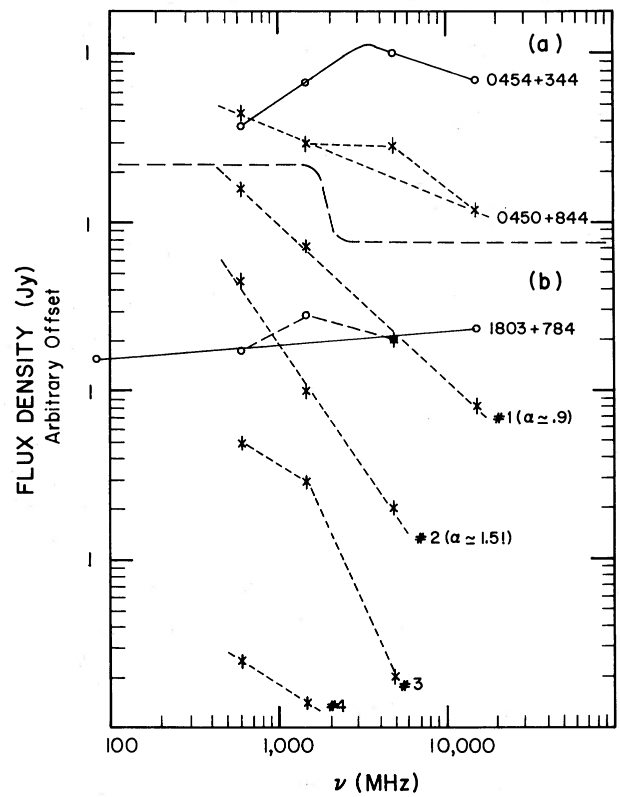

FIG. 1.—The radio spectra of the sources observed in (*a*) the field near 0454+844 and (*b*) the field near 1803+784. The flux density scale is in arbitrary units. The spectrum of 0450+844 indicates this emission may arise from the core of a radio galaxy. The spectral indices of the radio emission in the field of 1803+784 are much steeper indicating they are probably associated with a cluster of galaxies.

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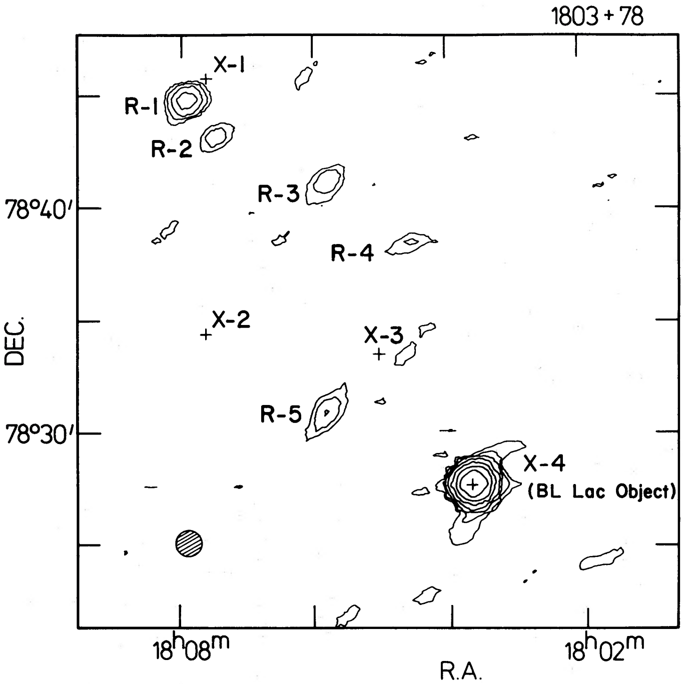

FIG. 2.—CLEANed 49 cm map of the field near 1803+784 showing components 1–5. The restoring beam is shown by a shaded ellipse. The contour levels are 0.8, 1.6, 3.1, 6.3, 12, 25, and 50% of the peak flux density which is 1745 mJy per beam area. The radio components are denoted by R-1 through R-5. The position of the X-ray knots, X-1 through X-4, (Biermann *et al.* 1982) are denoted by a +. Note that the BL Lac object which displays X-ray radio emission, 1803+784, is denoted by X-4. The only sources with nearly coincident X-ray and radio sources are the BL Lac object and R-1/X-1.

1807+787b agree quite well with that designated by Biermann *et al.* (1982) for the radio source associated with X-ray source 1 of 1803+784.

There does not appear to be anything significant on the POSS near the positions listed in Table 1 for 1807+787b and 1805+786. However, there is a relatively bright (17–18 mag) extended red galaxy ~30″ from component 1807+787a and another red stellar object ~18″ from component 1804+786. However, a deep CCD investigation of the optical emission near component 1807+787b, which is associated with the X-ray emission, reveals three faint objects whose positions are denoted by A, B, and C in Figure 4. Objects A and B are 22–22.5 mag, while C is >22.5 mag in the *R* filter. There is marginal evidence for extended emission from A. In this part of the sky, one expects 4 times as many galaxies than stars at this magnitude level (Kron 1980), implying that A, B, and C are galaxies.

IV. DISCUSSION

The X-ray/radio source 0450+844 appears to be associated with a background/foreground galaxy and can be understood as the active nucleus of a galaxy (17–18 mag) possibly dominating a cluster (several faint objects in vicinity of the optical galaxy on POSS). Assuming a flat radio spectrum and a +1 power law between high frequency radio and X-rays (Biermann *et al.* 1981) yields a bend in the millimeter range consistent with other compact nuclei. Figure 5 displays the spectrum. Conversely the radio spectrum ($\alpha = +0.4$) can be extrapolated from the radio to the optical. A bend in the spectrum corresponding to $\alpha = +1.4$ must then occur between the optical/X-ray. A survey of extragalactic X-ray sources shows that X-ray selected active galactic nuclei are more likely to display radio emission than an optically selected sample (Feigelson, Maccacaro, and Zamorani 1983). Further, Zamorani *et al.* (1981) find that radio-loud quasars are on the average 3 times more X-ray luminous than radio-quiet quasars. Radio surveys at 5 GHz (Katgert *et al.* 1973;

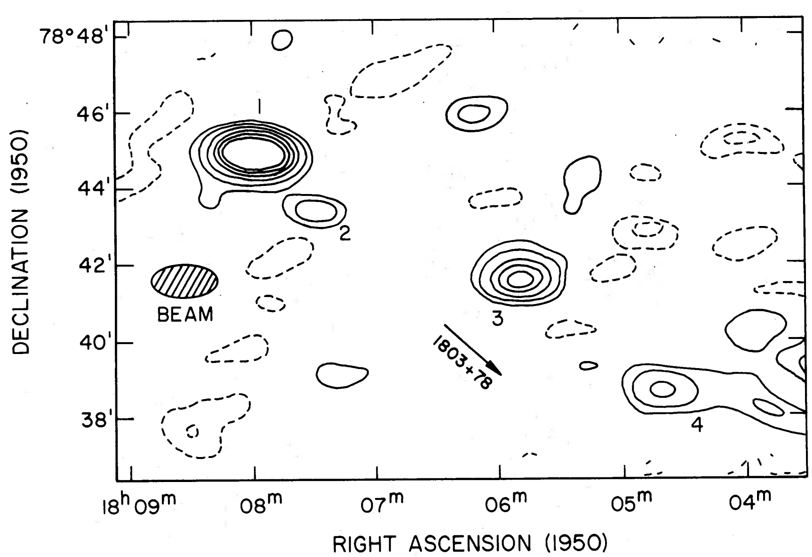

FIG. 3.—CLEANed 20 cm map of the field near 1803+784 showing components 1, 2, 3, and 4. The restoring beam is shown by the shaded ellipse. The contour levels are −2, 2, 4, 6, 8, 10, 25, and 50% of the peak flux density which is 290 mJy per beam area.

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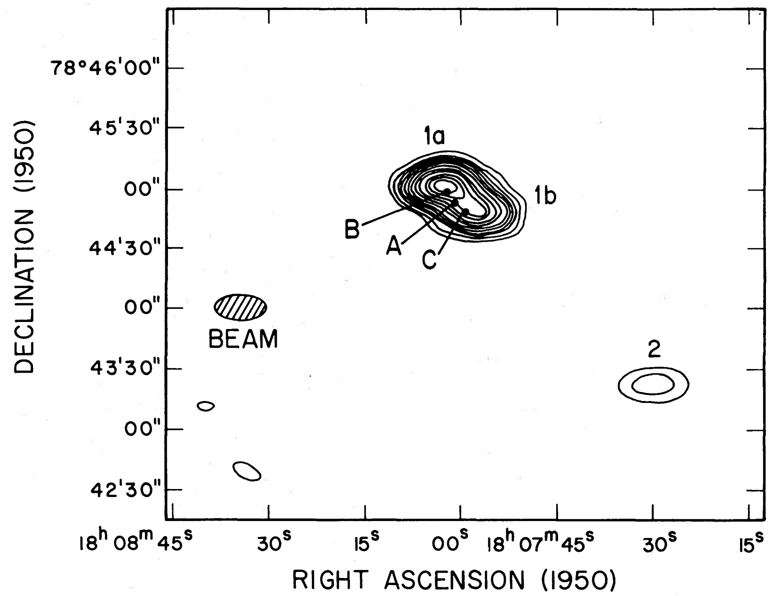

FIG. 4.—CLEANed 6 cm map of components 1 and 2 of the field near 1803+784. Note that component 1 is resolved into two components. The restoring beam is shown by the shaded ellipse. The contour levels are −5, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, and 90% of the peak flux density which is 12.6 mJy per restored beam.

Ulvestad *et al.* 1981) show that active galactic nuclei are compact in their radio emission and display a spectral index in the radio typical of that of 0450+844.

The morphology of the sources near 1803+784 appears to be a little more enigmatic. The radio emission near 1803+784 consists of at least four resolved components, (size > 10″) located along a p.a. ~35°, and all have very steep spectral indices. This emission is not associated with any single optical object that can be identified on the POSS. The position angle of alignment of the three principal radio components is misaligned by 23° with the compact radio source. Inspection of Figure 2 shows that in general the distribution of these sources is aligned with the compact radio source 1803+784.

One viable explanation for this emission is that it originates from a background cluster of galaxies which is beyond the magnitude limit of the POSS. These background sources are found to be >22 mag as the CCD investigation shows. The source at 1807+787b (X-ray source 1803+784 No. 1 Biermann *et al.* 1982) can be understood as radio emission from several superposed radio galaxies or a cluster with the galactic nuclei emitting the X-rays. The four sources 1804+786, 1805+786, and 1807+787a, b extend over ~12′. For $z > 0.5$, this corresponds to a linear size (Einstein-de Sitter model $H_0 = 75$) of >3.2 Mpc. Again Katgert *et al.* (1973) at 5 GHz find that most radio galaxies in clusters are dominated by extended radio emission. The radio spectral indices of all the sources are very steep, typical of cluster radio sources (Erikson, Matthews, and Viner 1978). Clusters with dominating galaxies are more likely to display X-ray emission (Gursky *et al.* 1972; Erickson, Matthews, and Viner 1978). A correlation between X-ray emission and radio power found by Erickson, Matthews, and Viner (1978) has been disputed by Ulmer *et al.* (1981). If this correlation were correct, it would seem to indicate that the X-ray emission originates from hot intracluster extragalactic gas. Adopting −23 to −25 as the plausible range of absolute magnitude for the active galaxies observed, we obtain estimates for the redshifts in the range 1–2. This redshift gives X-ray luminosities of about 10^{45} ergs s^{-1} consistent with an interpretation as free-free emission from hot intergalactic gas in a cluster.

Another possible origin for the X-ray emission is thermal bremsstrahlung and nonthermal emission associated with individual active galaxies in the cluster (Solinger and Tucker 1972). Inspection of Figure 4 shows that the structure of the radio emission is aligned with the three optical sources, suggesting that the optical/radio emission is related and may originate from active galaxies. The spectrum of 1807+787b is displayed in Figure 5. A spectral index of +0.7 fits the radio/optical/X-ray data. This spectrum looks typical of that associated with a radio-loud quasar such as 3C 446 or 3C 279 (Zamorani *et al.* 1981) which show structure on the arc second level at radio wavelengths (Ulvestad, Johnston, and Weiler 1982; Perley, Fomalont, and Johnston 1982). These objects display α_{ox} of +0.91 and +0.97, respectively, while 1807+784 is ~ +0.9. The radio emission from the other components (2–4) in the field of 1803+784 probably originates from other objects presumably extragalactic beyond the POSS plate limit. The compact radio source 1803+784 could possibly be a member of this cluster of galaxies.

This interpretation hinges on the identification of 1807+787b being identified with faint optical objects >22 mag. We do not as yet have any optical identification for other members of this complex radio field as evidenced by the 49 cm map (Fig. 2). Therefore we cannot yet dismiss the postulation of Biermann *et al.* (1982) that the X-ray/radio sources are physically associated with the compact radio source 1803+784 in a manner similar to that found in extended extragalactic radio sources.

A third possibility for the X-ray emission is the inverse Compton effect: Scattering of microwave background photons

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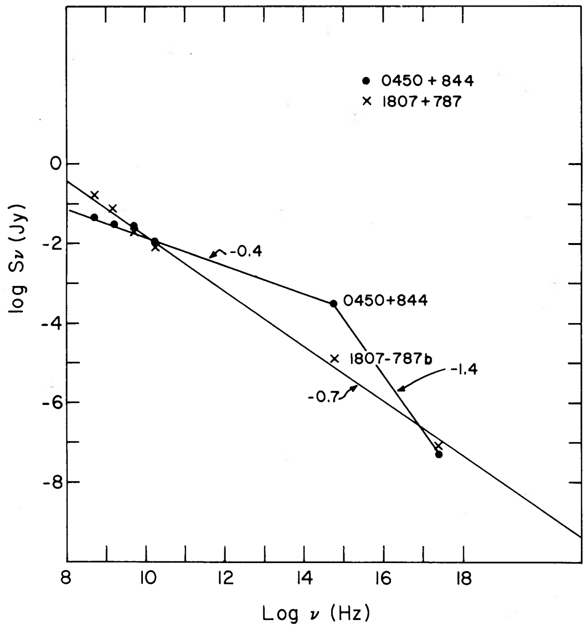

FIG. 5.—Flux density measurements at radio, optical (this paper), and X-ray (Biermann 1981) for 0450+844 and 1807+787 (components 1a, b). The spectral indices at radio wavelengths extrapolate well to optical wavelengths. Further the optical spectrum of 1807+784 extrapolates well to the X-ray indicating that it is probably a QSO while that of 0450+844 is steeper making it more typical of galactic nuclei.

can produce X-ray emission which is easily associated with steep spectrum radio sources without requiring departure from equipartition.

We suggest that the X-ray/radio sources near 0454+844 and 1807+787b may be associated with active galaxies. The energy mechanisms are probably the standard core-jet model in which the optical/X-ray emission originates near the nucleus via synchrotron or synchrotron-Compton mechanisms, while the radio emission occurs in a physically distinct outlying region (Zamorani *et al.* 1981). Sensitive optical, IR, and radio measurements are necessary to check these suggestions and investigate the other radio sources found in the field surrounding 1803+784. Optical identifications of the sources giving rise to the radio/X-ray emission will allow the unambiguous determination of the physical origin of this emission.

V. CONCLUSIONS

The radio emission from the X-ray/radio emission near the compact radio sources 0454+844 and 1803+784 has been measured at 49, 20, 6 and 2.8 cm and found to be non-thermal in origin. The radio/X-ray source (0450+844) within 2'.8 of 0454+844 has been identified as emanating from a background galaxy. The radio/X-ray emission in the field of 1803+784 is very complex. At least four radio components have been identified. The strongest radio source 1807+787b is found to be associated with faint (>22 mag) objects which may be galaxies. Thus the X-ray/radio emission may originate from members of a cluster of galaxies of which the compact radio source 1803+784 may or may not be a member. However, until more optical identifications are made for more radio/X-ray sources in the field of 1803+784, the original speculation by Biermann *et al.* (1982) that the X-ray/radio sources are physically associated with the compact radio source 1803+784 in a manner similar to extended extragalactic radio sources cannot be ruled invalid.

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