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OBSERVATIONS OF SIX FLAT SPECTRUM SOURCES FROM THE 5 GHz SURVEY

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ABSTRACT

We wish to report observations at radio, optical, and X-ray wavelengths of six sources from the Bonn-NRAO 5 GHz survey. The sources were selected on the basis of their flux densities and spectral indices at 5 GHz. All have been shown to contain compact radio cores and to emit strongly at X-ray wavelengths; five are strongly polarized at optical wavelengths. The measured flux densities suggest that the sources are of comparable luminosity (per fractional bandwidth) in the X-ray and optical regions. The interpretation of these results in terms of a synchrotron–self-Compton mechanism is briefly discussed.

Subject headings: BL Lacertae objects — quasars — radio sources: general — X-rays: sources

I. INTRODUCTION

In this *Letter* we report early results of a study of the properties of radio sources initially discovered in the relatively high frequency (5 GHz) Bonn-NRAO survey. The present results are for six strong sources (0212 + 73, 0454 + 84, 0716 + 71, 1803 + 78, 1928 + 73, and 2007 + 77) selected from the S5 north polar region survey (Kühr *et al.* 1981*a*) on the basis of (a) flux density ($S >$ 1 Jy), (b) spectral index ($\alpha > -0.2$ between 2.7 and 5 GHz, where $f_\nu \alpha \nu^\alpha$), and (c) positional coincidence with a stellar object on the Palomar Observatory Sky Survey (POSS). The new observations, which include studies at radio, optical, and X-ray frequencies, are reported below.

II. OBSERVATIONAL RESULTS

a) *Radio Data*

In Table 1 we list the catalog values of flux density at 6 cm and the spectral index between 11 cm and 6 cm (Kühr *et al.* 1981*b*). Also listed are the ranges in observed flux density at 2.8, 6, and 11 cm derived from measurements at various epochs between 1977 February 5 and 1980 May 30. The relevant calibration procedures are discussed by Kühr *et al.* (1981*a*). The sources are all quite variable, the relative changes ranging from 7% in 1928 + 73 to 250% in 0716 + 71 at a wavelength of 2.8 cm. The data are not, however, sufficient to establish characteristic time scales for these changes.

High angular resolution studies were carried out at the VLA and with VLBI techniques, using the Bonn, Haystack, NRL, Greenbank, Ft. Davies, and Owens Valley antennas in various configurations. All measurements were made at a wavelength of 6 cm, and the results are summarized in Table 1. The sources appear to be unusually compact. With the exception of 0716 + 71, none of the sources has components of size exceeding 0".5 and flux density exceeding 5% of the total. In earlier surveys of compact sources (see Weiler and Johnston 1980; Perley, Fomalont, and Johnston 1980), approximately 30% of the sources display structure extending beyond 1". All six of the present sources have at least 50% of their flux in components smaller than 2 milli-arcsec (mas); essentially all the flux from the sources 0454 + 84, 0716 + 71, and 1803 + 78 is contained within components extending over less than 5 mas. These sources are thus among the most compact yet studied by VLBI.

The radio polarization of 0716 + 71 was also measured at the VLA as 1.1% in position angle (P.A.) 99° (Perley, Fomalont, and Johnston 1980).

b) *Optical and Ultraviolet Observations*

Table 2 contains the results of optical photometric, spectroscopic, and polarimetric observations of the six sources. The photometric data were obtained mainly with the 340/500/1375 mm Schmidt telescope and the 300/1500 mm astrograph at the Hoher List Observatory. Comparison stellar sequences were taken from the SA4 region (Häegkvist 1973) and from Wing (1973). It is clear from the comparison between estimates from POSS and the present results that 0716 + 71 is variable and that 0454 + 85 and 1928 + 73 probably are variable.

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TABLE 1

RADIO DATA

Source	Cat. S_6 α_6	Flux Density Range λ (cm)	S (Jy)	VLBI Measurements at 6 cm[a] S_{Total} (Jy)	$S_{Compact}$ (Jy)	Size (mas)	Comments
0212 + 73	2.20	2.8	2.40[b]				
	− 0.12	6	2.37–2.45	2.36	1.51	1.2	Observed: 1979 Dec 7
		11	2.38[b]				
0454 + 84	1.39	2.8	1.35–1.54				
	+ 0.38	6	1.12–1.57	1.25	1.31	0.8 × 0.4	Extension P.A. 150°
		11	1.06–1.15				Observed: 1979 Dec 7
0716 + 71	1.12	2.8	1.27–2.28		0.5	< 1	Double: separation 1.3 mas in P.A. 10°[c]
	+ 0.21	6	0.65–1.12	0.65			Observed: 1979 Dec 7
		11	0.88–1.09		0.16	< 1	
1803 + 78	2.62	2.8	2.31–2.82		1.7	< 1	Double: separated by 1.2 mas in P.A. 112°
	+ 0.26	6	2.07–2.62	2.30			Observed: 1979 Dec 7
		11	2.20–2.33		0.7	3.7 × 1.9	Extension P.A. 20°
1928 + 73	3.34	2.8	2.90–3.52		1.37	< 1	Components coincident
	− 0.01	6	3.15–3.46	3.51			Observed: 1980 Aug 2
		11	3.36–3.38		0.76	1.7 × 0.3	Extension P.A. 157°
2007 + 77	1.26	2.8	0.97–1.98		1.17	< 0.5	Double separation 1 mas in P.A. 84°
	+ 0.68	6	1.11–1.79	1.50			Observed: 1980 Aug 2
		11	0.75–0.93		0.25	< 0.5	

[a]The errors in individual component flux densities is of order ±10%; S_{Total} and $S_{Compact}$ are estimated independently.
[b]Single measurements only.
[c]A VLA map of 0716 + 71 shows ~ 10% of the total flux density in extended components at P.A. 30° (Perley, Fomalont, and Johnston 1980).

TABLE 2

OPTICAL AND X-RAY OBSERVATIONS

Source	Optical M_{pg} POSS Present	P (ΔP) (%)	θ ($\Delta\theta$) (degrees)	Date	X-Ray Counts[a] (Error)	Time (S)	Energy (keV)	Flux (mJy)	Comments
0212 + 73	19	7.8	96.8	1981 Feb 2	190	2574	0.3–3.1	227	BL Lac (?)
	19[b]	(±1.9)	(±7.1)		(±14)				
0454 + 84	16.5	18.5	49.8	1980 Jan 13	17	1444	0.3–2.0	51	BL Lac
	18[b]	(±2.2)	(±3.4)		(±5)				
0716 + 71	13.2	13.9	11.1	1979 Aug 29	208	2415	0.2–3.5	220	BL Lac
	15.5	(±1.2)	(±2.4)		(±15)				
		28.6	162.5	1980 Jan 14					
		(±0.3)	(±0.3)						
1803 + 78	16.4	35.2	96.2	1979 Aug 28	103	1966	0.15–2.7	155	Weak emission line
	17[b]	(±0.4)	(±0.3)		(±11)				at λ4650 BL Lac (?)
1928 + 73	15.5	0.75	163	1979 Dec 21	204	1671	0.2–3.5	325	QSO, $z = 0.36$
	16.5	(±0.4)	(±1.5)		(±15)				
2007 + 77	16.7	15.1	87.4	1979 Aug 28	127	3029	0.25–4.0	107	BL Lac
	17	(±0.9)	(±1.7)		(±13)				

[a]The X-ray counts were derived by counting photons inside a circle of radius 120″; the effective observing time has been corrected for dead time (factor of 1/1.04) and the finite size of the circle used (factor of 0.85) and is thus 0.85/1.04 times the "time in processed image." The background was derived in all cases from a concentric circle of radius 120″–400″. The flux densities were derived using a power-law spectrum with an assumed photon-index of −1.5, and apply strictly only to the energy range indicated in column 8.
[b]Steward Observatory estimates from polarimetry.

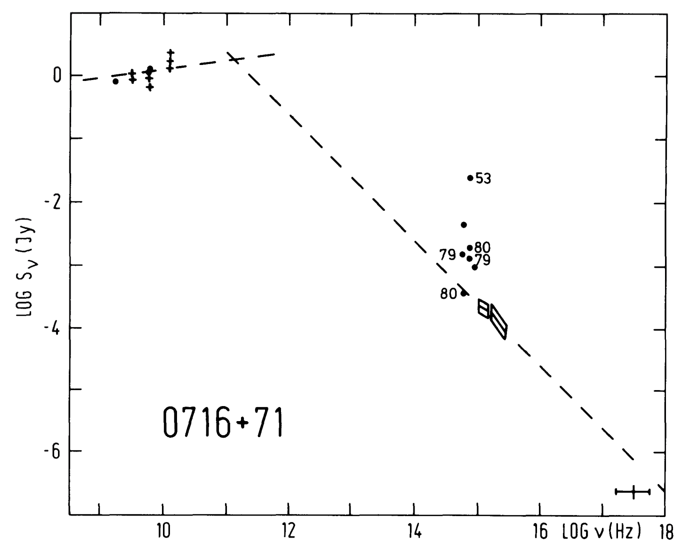

FIG. 1.—Flux density measurements at radio, optical, ultraviolet, and X-ray wavelengths for object 0716 + 71. For comparison a power-law spectrum of index $\alpha = -1$ is also shown.

Polarimetric and spectroscopic observations have been carried out at the Steward Observatory 2.3 m telescope; the results are also listed in Table 2. Five of the six objects for which data could be obtained are strongly polarized and one of them, 0716 + 71, is clearly variable. The polarization for 1803 + 78 is among the highest ever measured for a compact extragalactic source. In addition, for both 1803 + 78 and 2007 + 77, polarization measurements made in two intermediate bands (λλ3400–4600, λλ7150–8660) indicate the polarization is independent of wavelength in this region. Spectroscopic data for four of the objects were obtained using the Boller and Chivens spectrograph and the Reticon detector system. They show that 0454 + 84, 0716 + 71, and 2007 + 77 have essentially featureless spectra in the range 4000–7500 Å. The spectrum of 1803 + 78 is similar but shows evidence of a broad weak feature at $\lambda \sim 4650$ Å; two spectrograms were obtained of this object in order to confirm this feature. The source 1928 + 73 is a normal QSO with a redshift $z \sim 0.36$. We conclude that 0454 + 84, 0716 + 71, and 2007 + 77 are BL Lac objects and that 0212 + 73 and 1803 + 78 probably are also.

Details of the *IUE* satellite measurements are described in Schleicher, Fricke, and Kollatschny (1980). Data were obtained only for one object, 0716 + 71, in both the long and the short wavelength regions. The flux densities are 1.8×10^{-4} Jy at 2000 Å and 2.4×10^{-4} Jy at 3000 Å, with a probable error of about 30%. No emission lines were detected, which is consistent with the suggested BL Lac nature of this object.

c) The X-Ray Data

Data were obtained for all six objects with the IPC imaging telescope aboard the *Einstein* satellite (see Table 2. In all cases an unresolved source was clearly detected at the radio/optical position; the sources thus are smaller than 1′. No evidence was found either for strong, low-energy (< 1 keV) absorption or for marked variability. The flux densities given in Table 2 are uncertain by about 30% and were derived assuming a photon spectral index of −1.5.

Figure 1 shows flux density measurements at radio, optical, ultraviolet, and X-ray wavelengths for object 0716 + 71. A power-law spectrum of index $\alpha \sim -1$ is also shown for comparison. Such a spectrum provides a crude overall fit to the data for all six sources, although the local spectral index in any one wavelength region usually differs significantly from this broad average value. The sources thus emit energy at comparable rates (per fractional bandwidth) at widely separated wavelengths.

III. DISCUSSION

The present study of flat spectrum radio sources has produced a relatively high proportion of strongly polarized objects at optical wavelengths and of very compact radio structures; it has also resulted in a 100% X-ray detection rate at relatively high flux levels. The significance of these results is rather more difficult to assess in view of the small and still incomplete sample involved and the consequent possible influence of selection effects. It appears that the fraction of BL Lac objects is unusually high in the S5 sample compared, for example, to a similarly defined sample from the S4 region (Kühr 1980). The X-ray detection rate is consistent with the hypothesis that the strong, flat spectrum radio sources are generally also strong X-ray emitters. It is also consistent with the conclusion of Zamorani *et al.*

(1981) that, among QSOs, the strong radio sources also tend to be stronger X-ray emitters. The present data do not, however, permit us to assess to what degree the detection rate has been influenced either by (a) the number of BL Lac objects in the sample, since these are generally also strong X-ray emitters; or (b) the ultracompact nature of the cm wavelength radio structures.

The approximate equality of the X-ray and optical luminosity per fractional bandwidth among these sources is also of interest. For the present sample, the value of $R_{xo} \sim (\nu_x f_x)/(\nu_o f_o)$ lies in the range $0.1 \lesssim R_{xo} \lesssim 1$, where ν and f denote frequency and flux density, respectively, and subscripts x and o refer to the X-ray and optical regions. Such values of R are not uncommon among QSOs generally (Zamorani *et al.* 1981) and, of course, depend somewhat on the frequencies chosen, unless the local spectral index is close to unity. From the cm wavelength radio spectral indices, it appears that the flux density at mm wavelengths may well satisfy $R_{or} \sim 1$, where subscript r refers to the mm region.

In view of the compactness of these sources as observed in radio wavelengths (and inferred from variability in the optical), it is tempting to ascribe the X-ray emission to the synchrotron–self-Compton (SSC) mechanism (see Jones, O'Dell, and Stein 1974; Riegler, Agrawal, and Mushotzky 1979). This mechanism does not of itself predict a ratio $R \sim 1$; this value is, however, predicted in certain classes of the SSC model. Thus, for example, in the spinar model of Pacini and Salvati (1978), in which the original energy flux in very low frequency electromagnetic radiation is supposed, first, to accelerate particles which, in turn, lose their energy by synchrotron emission in the magnetic field associated with the low-frequency spinar radiation, the self-Compton and synchrotron luminosities are necessarily of the same order. While this interpretation is not unique, the association of very compact sources of nonthermal (presumably synchrotron) emission with approximately equal optical and X-ray luminosities is certainly suggestive. Further X-ray and optical observations of compact radio sources are, however, required to confirm the effect.

Finally, we should note that the position angle of optical polarization is roughly parallel to the direction between the individual components measured by VLBI techniques for the three sources, 0716 + 71, 1803 + 78, and 2007 + 77, in which such structure is observed. This alignment is in the same sense (***E*** vector parallel to structure) as that observed by Stockman, Angel, and Miley (1979) for normal (low optical polarization) QSOs with extended radio structure. The radio polarization for 0716 + 71 measured with the VLA is approximately perpendicular to this direction (***H*** vector parallel to structure) which is again similar to results generally obtained for extended sources. These results, if confirmed, may provide important constraints on the structure of compact radio sources.

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