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Letter to the Editor

Westerbork Observations of Flat Spectrum Galaxies in the 5 GHz 'S4' Survey

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Summary

Observations made with the Westerbork Synthesis Radio Telescope at 6 cm and 21 cm λ are reported for a complete sample of sources from the NRAO-Bonn 'S4' survey at 5 GHz that have flat high frequency spectra and are identified with galaxies. Most of the brighter galaxies in the survey appear to be related to BL Lac objects. The BL Lac galaxy 1101+38 has been found to have an extended radio component of ∿ 3'arc associated with it. An extended component located only on one side of the nucleus has been found in the case of 0309 + 41, which is identified with an 18^m galaxy.

Key words: Radio galaxies, BL Lac objects, optical identifications.

In high frequency radio surveys a large fraction of the sources are found to have relatively flat radio spectra ($\alpha > -0.5$; $s \propto \nu^{\alpha}$). Most of these are identified with QSOs, but a small fraction of the flat spectrum population is identified with galaxies. It is important to study this class of sources, particularly because some of the galaxies appear to have properties intermediate between normal galaxies and the highly active QSOs and could thus lead to an understanding of the relation between the two. In order to determine the brightness distributions of sources in the recent 5 GHz NRAO-Bonn 'S4' survey (Pauliny-toth et al. 1978) we have observed about 190 sources with the Westerbork Synthesis Radio Telescope (WSRT) at 5 GHz. We report here the observations of a complete subset of these sources, namely those with flat radio spectra ($\alpha > -0.5$ between 2.7 and 5 GHz) that were identified in the S4 survey with galaxies. We have observed these sources also at 1415 MHz. Apart from providing improved optical identifications the observations have revealed interesting extended structures associated with some sources.

Observations and Results

For the observations at 6 cm each source was observed for about 2 minutes at each of three different hour angles, and the data transformed to produce a map. The details of the observations and reduction will be presented elsewhere. The radio positions and angular structure are listed in Table 1. None of the sources, except for 0010+40, was resolved by the 6" arc beam of the WSRT and only an upper limit to the angular size is given based on model fits to the observed visibility functions. The radio positions are estimated to be accurate to about 0".5 arc. The optical identification data is summarized in columns 7 to 9 of Table 1. References to previously proposed identifications and finding charts were taken from the compilation of Véron and Véron(1974 (An updated version of the compilation was kindly supplied by Dr. Véron). Accurate optical positions are available for most of the sources and were measured by us for 1732+38 and 1745+62. These optical positions and corrections to previously proposed identifications for 0010+40 and 0309+41 are given in the notes to Table 1. In addition to the sources in Table 1 there are six other well known flat spectrum sources in the S4 survey identified with galaxies. These are listed in Table 2.

Structures at 21 cm

As the 5 GHz observations were relatively insensitive to the presence of weak or extended components of steeper spectral indices we also made observations with the WSRT at the lower frequency of 1415 MHz. In additio to the sources listed in Table 1, the source 1101+38 was included in these observations consisting of 5 cuts each of 5 to 10 minutes duration and suitably spaced in hour angle in order to obtain a fairly uniform distri-

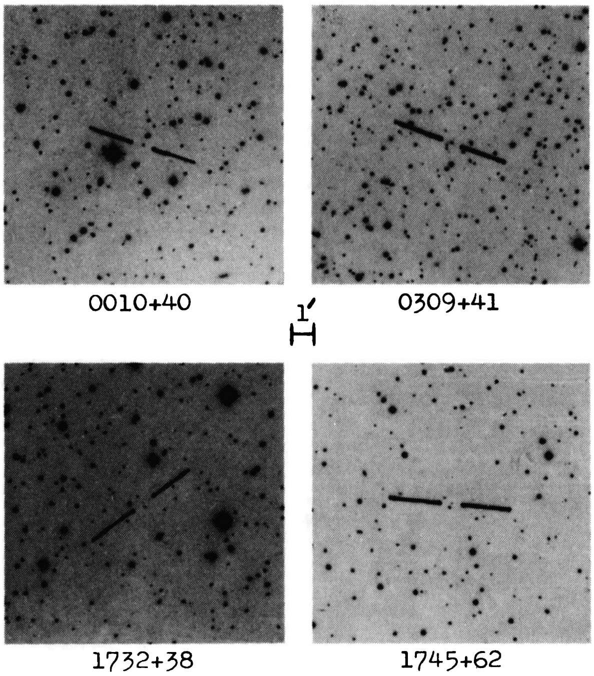

Fig. 1. Finding charts reproduced from the E prints of the Palomar Sky Survey. North is to the top and East to the left.

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Table 1. Radio Positions, Structures and Optical Identifications

Source 'S4'	Radio Position (1950.0) RA h m s	DEC	Flux Density 5 GHz (Jy)	Flux Density 1.4 GHz (Jy)	Radio Structure ("arc)	mag.	Ref. Finding Chart	Ref. Optical Position
0010+40	00 10 54.26	40 34 57.2	1.100±0.04	1.617±0.06	a	17.9	P	1[a]
0218+35	02 18 04.14	35 42 32.3	1.097±0.03	1.292±0.05	<2	20	2	2
0309+41	03 09 44.79	41 08 49.0	0.456±0.03	0.500±0.03[b]	<2[b]	18	P	3[b]
0402+37	04 02 29.85	37 55 27.4	1.114±0.03	1.580±0.06	<2	18.5	4	4
0733+59	07 33 11.64	59 47 48.4	0.576±0.03	0.570±0.03	<2	14.9	1	1
0831+55	08 31 04.44	55 44 41.5	5.785±0.06	7.920±0.40	<1	18.5	5.6	7
1146+59	11 46 10.44	59 41 36.7	0.615±0.03	0.350±0.02	<2	12.5	8	8
1356+47	13 56 43.06	47 52 30.2	0.464±0.03	0.600±0.03	<2	19.5	9	9
1732+38	17 32 40.44	38 59 47.3	0.879±0.03	0.632±0.03	<2	19	P	P[c]
1745+62	17 45 48.05	62 27 55.8	0.762±0.03	0.808±0.04	<2	19.5	P	P[d]
2323+43	23 23 18.34	43 30 28.9	0.983±0.03	1.744±0.07	<2	18	10	3
2351+45	23 51 49.98	45 36 23.0	1.275±0.03	2.070±0.09	<2	20	1	1
2352+49	23 52 37.77	49 33 27.0	1.855±0.04	2.414±0.09	<2	19	6	7

References: P. Present work; 1. Cohen et al. (1977); 2. Johnson (1974); 3. Edwards et al. (1975); 4. Wills et al. (1973); 5. Véron (1971); 6. Fanaroff & Blake (1972); 7. Véron & Véron (1975); 8. Condon & Dressel (1978); 9. Kühr (1977); 10. Gearhart et al. (1973)

[a] 0010+40: Observed at only 2 position angles at 5 GHz. About 80% of the flux is in a component <2" and the rest in an extended component (possibly a halo) of size 10 to 15". The radio position of the compact component differs by ∿7" from that given by Cohen et al. (1977) who considered the source to be in an empty field. The accurate optical position measured by them for a $17^m.9$ red stellar object lies within 0".5 of our radio position and is therefore the right identification. A finding chart is given in Fig. 1.

[b] 0309+41: At 21 cm λ 70% of the total listed flux density arises in an unresolved component and the remaining in an extended component (Fig. 2). The source was considered by Edwards et al. (1975) to be in an empty field. However, the radio position measured by them with the NRAO 3 element interferometer lies about 20" away from the compact component. The accurate optical position reported by them for a nearby object (18^m galaxy) is in excellent agreement with the radio position of the compact component and this galaxy is therefore the right identification. A finding chart is given in Fig. 1.

[c] 1732+38: The optical position of the identified galaxy (finding chart in Fig 1) is $17^h32^m40^s.57 \pm 0^s.1$; $38^o59'46".6 \pm 1"$.

[d] 1745+62: The optical position of the identified galaxy (finding c hart in Fig 1) is $17^h45^m48^s.34 \pm 0^s.15$; $62^o27'56".1 \pm 1"$

bution of position angles on the sky. The data were transformed to produce maps and CLEANed using the standard reduction package at Leiden. The measured flux densities at 21 cm are listed in column 5 of Table 1.

Additional radio components within 5' arc of those observed at 5 GHz were detected in four sources. In the case of 0010+40 and 2323+43 these components are unresolved (size < 20" arc) and are located 217" arc (at $\alpha = 00^h10^m36^s.56\pm0^s.1$, $\delta=40^o36'18".5\pm1".5$; $S_{21cm}=0.130\pm0.01$ Jy) and 142"arc (at $\alpha=23^h23^m06^s.14\pm0^s.1$, $\delta=43^o29'59".1\pm1".5$; $S_{21cm} = 0.133 \pm0.01$ Jy) respectively from the unresolved nuclear components. As no extensions or bridges of emission were detected in either case, the physical association of these components with the galaxies cannot be considered certain. Contour maps for the other two sources (0309+41 & 1101+38) with an angular resolution of 24" in RA and 24" cosec δ in DEC are shown in Fig. 2.

The additional component of 0309+41 appears resolved, with its peak intensity (at $\alpha = 03^h\ 09^m\ 41^s.14 \pm 0^s.2$, $\delta = 41^o10'06" \pm 2"$) ∿ 87" arc away from the compact component. No significant emission, to a limit of ∿10 mJy/ beam area, was detected on the opposite side of the galaxy. As the source does not appear in the 4C catalogue the extended component has a spectral index flatter than −1.3 between 178 MHz and 1.4 GHz. Between 2.7 GHz and 10 GHz the source has an inverted spectrum so that the nuclear component is likely to be opaque at these frequencies. The source thus appears to belong to the D2 classification of Miley (1971) of which 3C273 is the standard example. D2 sources are characterised by a compact flat spectrum component coincident with the optical object and a one sided extended component of steeper spectral index. Although several QSOs (e.g.3C345 & 454.3; Davis et al. 1977) are known to belong to this class, 0309+41 appears to be the first example of a galaxy in this class. Optical observations are necessary to determine the nature and redshift of the galaxy(18^m) identified with this source.

The extended emission in 1101+38 (an elliptical galaxy with a BL Lac nucleus, Ulrich et al. 1975) accounts for ∿ 29% of the total flux density of 0.85 ± 0.04 Jy at 21 cm λ. The structure appears to be elongated with its surface brightness decreasing away from the central component. The total extent of the emission to the lowest contour shown in Fig. 2 is ∿ 3'.5 arc, corresponding to a projected linear size of ∿ 190 kpc (for H_o= 50 km s^{-1} Mpc^{-1}) at the redshift of 0.0308. The true extent of the source could be even larger as the present observations are sensitivity limited. The source does not appear in the 4C catalogue so that the extended component has $\alpha > -1.0$ at low frequencies. The compact nuclear component has an inverted spectrum between 5 GHz and 10 GHz.

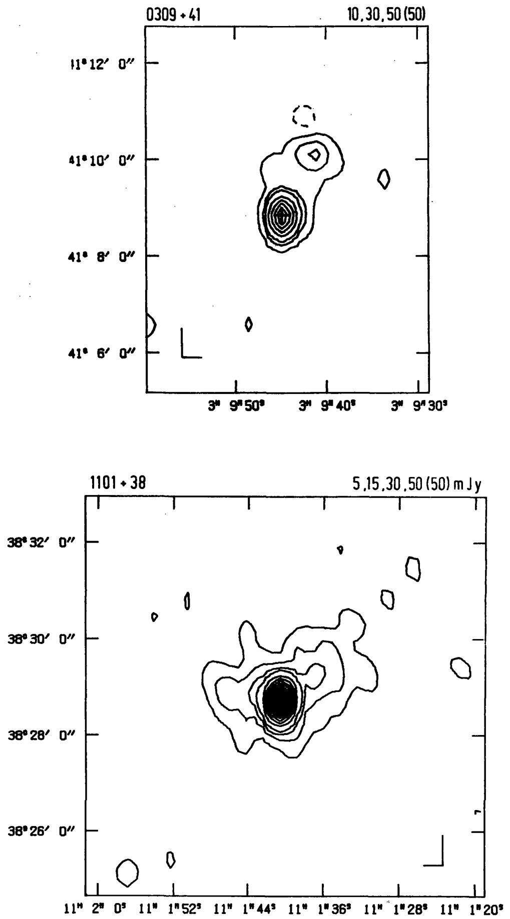

Fig.2. Contour maps at 21 cm λ. The first few contours and the subsequent contour interval (in brackets) in mJy/beam area are marked on the right hand top. The first negative contour is shown dotted. Crosses represent the positions of the galaxies. Half power beam sizes are shown by the L spapes at the bottom.

Table 2.	Other flat spectrum galaxies in S4	
Source	Other name	Ref. to BL Lac nature
0316+41	NGC 1275	Véron (1978)
1101+38	Markarian 421	Ulrich et al. (1975)
1625+39	Markarian 501	Ulrich et al. (1975)
1743+55	NGC 6454	Ulrich et al. (1975)
1807+69	3C 371	Miller (1975)
2200+42	BL Lac	

Discussion

In addition to the sources listed in Table 1 the other six flat spectrum sources in the S4 survey (Table 2) are all identified with bright galaxies with $m_{pg}<15$. It is interesting to note that these include the object BL Lac and that the other five galaxies appear

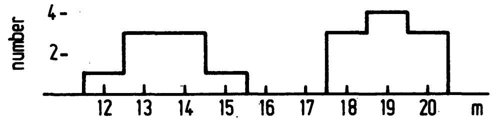

Fig.3. Distribution of optical magnitudes for all the flat spectrum galaxies in the S4 survey.

to be related to the class of BL Lac objects. References where this relation has been pointed out are given in Table 2. Except for NGC 6454, all the other sources show nonthermal optical activity in their nuclei. There are two sources in Table 1 that are identified with bright galaxies (m_{pg} < 15); 0733+59, an elliptical galaxy with an apparently bright nucleus and 1146+59 (NGC 3894), an S0 galaxy. Optical observations are required to see if these are also related to the BL Lac phenomenon.

Very few BL Lac objects are known to contain extended double structure of the type found in radio sources identified with elliptical galaxies and quasars. The best known example is that of 1400+162 (Baldwin et al. 1977) which apart from a compact nuclear component has a well collimated double structure typical of steep spectrum galaxies and quasars of high radio luminosity (class II sources of Fanaroff and Riley, 1974). Because of its smaller redshift the galxy 1101+38 has considerably lower total luminosity and the extended radio emission associated with it is also typical of lower luminosity radio galaxies (class I) in which the double structure is not always well collimated. In both these sources the emission at lower frequencies ($\lesssim$ 400 MHz) would be dominated by the extended lobes. As most BL Lac objects have been mapped only at high frequencies where the nuclear component dominates this could at least partly explain the absence of extended structure around them. Several BL Lac objects have fairly steep spectra at low frequencies (e.g. Altschuler and Wardle 1975) and high resolution mapping at low frequencies is needed to obtain unbiased data on extended structures associated with them. The present observations of 1101+38 strengthen the growing belief that BL Lac objects are not a fundamentally different class of objects from radio galaxies and QSOs.

Most of the objects in Table 1 are identified with galaxies fainter than 18^m. Little is known about the nature of these galaxies. Although it is possible that a few are QSOs misidentified as galaxies, most of them appear to be definitely non-stellar on the PSS prints. It is also worth noting that they are at least 3 magnitudes fainter than the brighter flat spectrum galaxies in the S4 survey as can be seen from the magnitude distribution of all the sources (except 0010+40) in Tables 1 and 2. The lack of continuity in the magnitude distribution may imply two different class of objects. Optical spectroscopic observations are clearly needed to investigate the nature of the fainter objects.

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