VLA observations of 20 FR II radio sources at 8.4 GHz

Ilias Fernini¹

Received: 10 April 2019 / Accepted: 26 September 2019 / Published online: 4 October 2019
© The Author(s) 2019

Abstract We report the last observational paper of hot spots for 20 Fanaroff-Riley class II (FR II) sources. These sources are part of a large sample of 98 FR II to study the unification scheme of FR II radio galaxies (RGs) and quasars (QSRs) using the hotspots (HSs) location and morphology. High-resolution VLA observations at 8.4 GHz were conducted for the whole sample. The investigation of HSs properties in FR II radio sources is essential for a better understanding of the dynamics related to the objects and their impact on the surrounding environment. HSs were classified into edged and recessed types, where the former is located at a radio lobe's outer edge, and the latter is embedded within the lobe. The present sub-sample contains 12 RGs and 8 QSRs. Radio contour maps for each source were presented using the VLA in its A and B configurations. In total, we have identified 18 HSs for these 20 radio sources. The 12 RGs possess 8 edged HSs and 2 recessed HSs. The 8 QSRs possess 6 edged HSs and 2 recessed HSs. Out of the 14 edged HSs, RGs and QSRs possess $\sim 57\%$ and $\sim 43\%$, respectively. A thorough morphological discussion of the 20 sources with their HSs is presented in the present work.

Keywords Hot spots · Radio galaxies · QSRs

1 Introduction

To conduct a compelling exploration of the properties of radio galaxies, it is first essential to discuss their foundational elements and relationship to hotspots (HSs). With regard to this, Fanaroff and Riley (FR) (1974) highlighted the

key association between the relative positioning of low and high brightness regions in radio sources with the intensity of their luminosity. Studies about similar discussions have highlighted the significance of giant radio sources as having a linear size that is either greater than or equivalent to 1 Mpc and is commonly utilized in astrophysical investigations (Ishwara-Chandra and Saikia 1999).

The variances between the FR II radio galaxies (RGs) and the FR II quasars (QSRs) are very important as related to the unification scheme of Barthel (1989). From the analysis of relativistic beaming effects, the jets of FR II can reach relativistic speeds up to $0.5c$ out to the ends of the lobes (Meisenheimer et al. 1989). Hotspots are usually interpreted as the terminal shocks when the jet abruptly terminates at the end of the source (Blandford and Rees 1974; Bridle and Perley 1984). Often multiple hotspots are seen, reflecting either continued outflow after the shock or movement of the jet termination point: the overall hotspot region is sometimes called the hotspot complex (Leahy et al. 1997).

This research is a component of existing literature (Fernini 2002, 2007, 2012, and 2014; hereafter F02, F07, F12, and F14) that falls under the study of HSs in a sample of 98 FR II sources. The primary purpose is to provide high-quality VLA images at 8.4 GHz of the HSs to better comprehend their importance in radio source models. As mentioned above, the classical picture of FR IIs defines HSs as bright radio emission near the end of each jet. However, it was reported in F02, F07, F12, and F14, that some HSs were either edged (located at the outer limb of the radio lobes) or recessed (embedded inside them). For the 78 FR IIs (40 RGs and 38 QSRs) discussed in F02, F07, F12, and F14, we were able to identify 111 HSs (75 edged and 36 recessed). For the 40 RGs, 61 HSs were designated with 19 recessed and 42 edged. For the 38 QSRs, we have identified 50 HSs with 17 recessed and 33 edged. A preliminary observational conclu-

✉ I. Fernini
ifernini@sharjah.ac.ae

¹ Department of Applied Physics & Astronomy, University of Sharjah, Sharjah, United Arab Emirates

Table 1 Basic properties of the 12 radio galaxies

IAU name	3C name	z	SLAS (arcsec)	l (kpc)	S_5 GHz (Jy)	Refs.
0411+14	4C 14.11	0.206	88	253.1	0.89	4, 6, 14, 18, 20
0832+14	4C 14.27	0.392	38	161.4	0.302	14
1251+159	3C 277.2	0.766	58	315.4	0.58	12, 14, 19, 24, 26
1254+476	3C 280	0.996	14.5	82.4	1.53	12, 14, 21, 24
1301+382	4C 38.35	0.470	28	129.5	0.21	1, 2, 3, 6, 11, 14
1343+500	3C 289	0.9674	10	56.6	0.60	10, 12, 14, 24
1419+419	3C 299	0.367	13	53.4	0.90	13, 14, 15, 22
1420+198	3C 300	0.27	100	344.1	1.10	12, 14, 16, 24
1540+60	3C 323	0.679	26	137.1	0.33	12, 14, 25
1626+278	3C 341	0.448	82	371.3	0.57	7, 12, 14
1627+234	3C 340	0.775	47	256.2	0.69	10, 12, 14, 24
1627+444	3C 337	0.635	43	222.4	0.91	10, 12, 14, 24

Notes. The different columns give the following information: (1) IAU source name; (2) 3C name; (3) known redshift; (4) source largest angular size in arcsec; (5) source linear size in kpc; (6) source extended flux at 5 GHz in Jansky; and (7) Refs.: (1) Allington-Smith (1982); (2) Allington-Smith et al. (1982); (3) Allington-Smith et al. (1985); (4) Becker et al. (1991); (6) Dixon (1970); (7) Gregorini et al. (1988); (10) Jenkins et al. (1977); (11) Katgert-Merkelijn et al. (1980); (12) Kellerman et al. (1969); (13) Kristian et al. (1978); (14) Laing et al. (1983); (15) Laing (1981); (16) Leahy and Williams (1984); (18) Peacock and Wall (1982); (19) Pedelty et al. (1989); (20) Perryman et al. (1984); (21) Pooley and Henbest (1974); (22) Riley and Pooley (1975); (24) Spinrad et al. (1985); (25) Strom et al. (1990); (26) Strom and Conway (1985)

Table 2 Basic properties of the 8 quasars

IAU name	3C name	z	SLAS (arcsec)	l (kpc)	S_5 GHz (Jy)	Refs.
1253+104	—	0.824	23.8	131.4	0.14	4, 8, 14
1258+40	3C 280.1	1.659	19.8	111.7	0.36	8, 12, 14
1317+520	4C 52.27	1.060	29.3	167.4	0.72	4, 6, 8, 14
1335−061	4C −06.35	0.625	11.1	57.1	0.98	6, 8, 14, 17
1422+202	4C 20.33	0.871	11	61.3	0.6	4, 6, 14, 23
1509+158	4C 15.45	0.828	9.1	50.3	0.4	4, 6, 9, 14
1530+137	4C 13.55	0.771	11.7	63.7	0.43	5, 6, 8, 14, 28
1545+210	3C 323.1	0.264	70.5	239.2	0.92	12, 14, 27

Notes. Same as for Table 1. Refs.: (4) Becker et al. (1991); (5) Binette et al. (1981); (6) Dixon (1970); (8) Hintzen et al. (1983); (9) Hutchings et al. (1988); (12) Kellerman et al. (1969); (14) Laing et al. (1983); (17) Lyne (1972); (23) Saikia et al. (1986); (27) Swarup et al. (1984); (28) Wills and Lynds (1978)

Table 3 VLA observations for the A- and B-configurations

Source (1)	Obs. date (2)	TOS (3)	VLA config. (4)	BW (MHz) (5)	Obs. date (6)	TOS (7)	VLA config. (8)	BW (MHz) (9)
4C 14.11	1995 Aug. 07	3580	A	12.5	1994 Jun. 23	3410	B	50
4C 14.27	1996 Dec. 15	3320	A	50	1997 Apr. 12	2840	B	50
3C 277.2	1994 Feb. 27	2680	A	25	1992 Jan. 11	2010	B	50
1253+104	—	—	—	—	1993 Mar. 02	2750	B	50
3C 280	1988 Dec. 22	2570	A	50	1994 Jul. 11	1580	B	50
3C 280.1	1991 Aug. 12	1660	A	50	1993 Mar. 02	2710	B	50
4C 38.35	2002 Mar. 21	1510	A	50	—	—	—	—
4C 52.27	1990 Apr. 11	1620	A	50	1994 Jul. 22	2480	B	50

Table 3 (Continued)

Source (1)	Obs. date (2)	TOS (3)	VLA config. (4)	BW (MHz) (5)	Obs. date (6)	TOS (7)	VLA config. (8)	BW (MHz) (9)
4C –06.35	1998 Mar. 02	3600	A	50	–	–	–	–
3C 289	1994 Feb. 27	1340	A	50	1994 Jul. 12	1600	B	50
3C 299	1988 Dec. 22	1750	A	50	–	–	–	–
3C 300	1995 Aug. 07	7140	A	12.5	1992 Jan. 11	1700	B	50
4C 20.33	1990 May 18	1700	A	50	–	–	–	–
4C 15.45	1990 Mar. 12	1130	A	50	–	–	–	–
4C 13.55	1995 Aug. 12	3460	A	50	–	–	–	–
3C 323	2007 Sep. 08	3830	A	50	–	–	–	–
3C 323.1	1991 Jun. 29	2220	A	50	1993 Apr. 02	1760	B	50
3C 337	1994 Feb. 27	2670	A	50	1994 Jul. 12	580	B	50
3C 340	1994 Feb. 27	2670	A	50	1994 Jul. 12	1600	B	50
3C 341	1996 Dec. 15	5040	A	25	1997 Apr. 13	2900	B	50

Notes. The different columns give the following information: (1) source name; (2) and (6) observation date; (3) and (7) duration of the observation in seconds; (4) and (8) VLA configuration (A or B); and (5) and (9) bandwidth in MHz

Table 4 Percentage of the flux recovered, rms noise, and beam size for the 20 radio sources at 8.4 GHz images

Source (1)	A images I image ($\mu\text{Jy beam}^{-1}$) (2)	A-beam (") (3)	Percent flux recov. (%) (4)	B images I image ($\mu\text{Jy beam}^{-1}$) (5)	B-beam (") (6)	AB images I image ($\mu\text{Jy beam}^{-1}$) (7)	AB-beam (") (8)	Percent flux recov. (%) (9)
4C 14.11	17	0.21	...	10	0.83	17	0.22	85
4C 14.27	14	0.24	...	30	0.82	10	0.33	95
3C 277.2	15	0.22	...	15	0.74	15	0.27	95
1253+104	...	...	...	40	0.74	...	...	85
3C 280	40	0.21	...	50	0.67	40	0.21	95
3C 280.1	25	0.40	...	40	0.69	50	0.54	96
4C 38.35	15	0.22	92	...	...	...	...	...
4C 52.27	15	0.20	...	50	1.20	25	0.24	90
4C –06.35	20	0.26	100	...	...	...	...	...
3C 289	35	0.21	...	25	0.67	45	0.35	85
3C 299	14	0.2	100	...	...	...	...	...
3C 300	25	0.23	...	12	0.75	15	0.25	85
4C 20.33	10	0.24	95	...	...	...	...	...
4C 15.45	15	0.22	95	...	...	...	...	...
4C 13.55	10	0.22	85	...	...	...	...	...
3C 323	12	0.24	90	...	...	...	...	...
3C 323.1	15	0.26	...	15	0.84	14	0.36	100
3C 337	15	0.24	...	20	0.7	15	0.29	96
3C 340	10	0.19	...	20	0.77	10	0.23	95
3C 341	25	0.23	...	20	0.99	20	0.35	90

Notes. The different columns give the following information: (1) source name; (2), (5) and (7) rms noise for the A, B, and AB images, respectively; (3), (6) and (8) beam size for the A, B, and AB images, respectively; (4) and (9) the percentage of the total flux density recovered for the images presented in the paper

Table 5 Beam size (arcsec), contour levels intensity (μJy per CLEAN beam area), and peak intensity (mJy/CLEAN beam area) for the 20 sources (A, B, and AB-configuration). All contours maps are drawn at -1 (dotted lines), 1, 2, 3, 4, 6, 8, 16, 32, 64, 128, 256, 512, and 1024

Source		A			B			AB		
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
4C 14.11	Fig. 1a	—	—	—	0.83	150	34.6	—	—	—
	Fig. 1 (b, c)	—	—	—	—	—	—	0.21	75	28.2
4C 14.27	Fig. 2a	—	—	—	0.82	100	5.52	—	—	—
	Fig. 2b	—	—	—	—	—	—	0.33	50	967
3C 277.2	Fig. 3a	—	—	—	0.74	75	82	—	—	—
	Fig. 3 (b, c)	—	—	—	—	—	—	0.27	75	47
1253+104	Fig. 4	—	—	—	0.74	150	21	—	—	—
3C 280	Fig. 5a	—	—	—	0.67	250	500	—	—	—
	Fig. 5b	—	—	—	—	—	—	0.21	250	308
3C 280.1	Fig. 6a	—	—	—	0.69	150	37	—	—	—
	Fig. 6b	—	—	—	—	—	—	0.54	250	26
4C 38.35	Fig. 7 (a, b, c)	—	—	—	—	—	—	0.22	75	2.35
4C 52.27	Fig. 8a	—	—	—	1.20	250	268	—	—	—
	Fig. 8b	—	—	—	—	—	—	0.24	250	233
4C -06.35	Fig. 9	0.26	100	86	—	—	—	—	—	—
3C 289	Fig. 10a	—	—	—	0.67	125	145	—	—	—
	Fig. 10b	—	—	—	—	—	—	0.35	250	100
3C 299	Fig. 11	0.20	100	125	—	—	—	—	—	—
3C 300	Fig. 12a	—	—	—	0.75	125	54	—	—	—
	Fig. 12 (b, c, d)	—	—	—	—	—	—	0.25	60	111
4C 20.33	Fig. 13	0.24	50	83	—	—	—	—	—	—
4C 15.45	Fig. 14	0.22	100	92	—	—	—	—	—	—
4C 13.55	Fig. 15	0.22	100	25	—	—	—	—	—	—
3C 323	Fig. 16	0.24	75	7.2	—	—	—	—	—	—
3C 323.1	Fig. 17a	—	—	—	0.84	100	50	—	—	—
	Fig. 17 (a, b)	—	—	—	—	—	—	0.36	75	46
3C 337	Fig. 18a	—	—	—	0.70	150	143	—	—	—
	—	—	—	—	—	—	—	0.29	75	58
3C 340	Fig. 19a	—	—	—	0.77	100	43	—	—	—
	Fig. 19 (b, c)	—	—	—	—	—	—	0.23	80	15
3C 341	Fig. 20a	—	—	—	0.99	150	8	—	—	—
	Fig. 20 (b, c)	—	—	—	—	—	—	0.35	90	3.3

Notes. The different columns give the following information: (1) beam size of the given configuration at 8.4 GHz; (2) the contour levels intensity per μJy per CLEAN beam area; and (3) gives the peak intensity in mJy per CLEAN beam area

sion is that the 78 sources have more edged hot spots than recessed. There is also a tendency for the RGs to have more edged (and recessed) HSs than the QSRs.

These results make the study of HSs and their locations essential for the models of radio sources where a HS is usually considered to be an edged HS. The location of a hot spot within the radio lobe is important in terms of the validity of the basic models of radio sources in which hot spots must always be at the outer edges of the radio lobes. Two plausible scenarios can be listed for

their recession. The first is that simple geometrical projection effects are the cause of their recession. Orientation effects may then play an essential role in explaining these observed hot spots properties (Gilbert and Riley 1999; Gilbert et al. 2004). The second scenario is that hot spots do not always coincide with the termination of the jets but are other features of the radio lobes (Bridle et al. 1994). The problem we would like to raise in this work is the following. If some preliminary results show that hot spots are not always found at the outer edges of the radio lobes (F02, F07,

Fig. 1 (a) 4C 14.11 with 0.83'' resolution from the B-configuration data; (b) northwestern lobe and (c) southeastern lobe of 4C 14.11 with 0.21'' resolution from the AB combined data (Table 5)

F12, and F14), is it possible to use their locations and sizes as observed in the RGs and the QSRs to differentiate between the two types of objects and use them as an orientation indicator?

This study is reporting the observations of 20 more FR II sources (i.e., 12 RGs and 8 QSRs). The focal point is on the general morphology of each source with a strong emphasis on the location of the HSs. A complete statistical analysis of the results obtained will be incorporated in future studies.

This paper is divided into the following sections. Section 2 reviews the selection criteria as well as the employed strategy in the observations regarding the calibration and data reduction. Further details regarding this review may be obtained through a thorough exploration of F14. In the third section, the method utilized for hotspot identification is discussed, and we give a detailed description of the observations of the 20 new radio sources. Section 4 summarizes the main results obtained for the 12 RGs and 8 QSRs con-

Fig. 2 (a) 4C 14.27 with $0.82''$ resolution from the B-configuration data; (b) 4C 14.27 with $0.33''$ resolution from the AB combined data (Table 5). The plus sign, here and in all other figures, indicates the position of the optical nucleus

cerning edged and recessed hotspots. This study has adopted standards of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$, and assumed a Friedmann-Robertson cosmology.

2 Methodology

2.1 Sample

The 20 FR II radio sources (12 RGs and 8 QSRs) have been drawn from the sample of Nilsson et al. (1993) that included 540 radio sources (267 radio galaxies and 273 quasars) with well-known FR II morphologies. The selection criteria have been fully explained in F14 and briefly summarized as follows: (i) Flux density: $S_{178 \text{ MHz}} > 5 \text{ Jy}$; (ii) Source Largest angular size (SLAS): $9'' \leq \text{SLAS} \leq 100''$; (iii) Redshift: $0.1 < z < 2.0$; and (iv) Declination: $-15^\circ \leq \delta \leq 80^\circ$. The

upper limit of 100 for the source largest angular size (SLAS) is seen to be different than in F14 due to obtaining a revised linear size for one source (3C 300). This source is noted to be the sole exception in the sample that has been seen to present a large angular size as described above. SLAS has been measured from hotspot to hotspot on the opposite sides. A summary of the basic radio properties pertaining to the 12 RGs and 8 QSR has been illustrated in Table 1 and 2, respectively.

2.2 Observations and data reduction

We originally intended to have typical integration times for each object in the A and B configurations in between 1.5 hours and 1 hour, respectively. The VLA archive data was used to complement our observations. This explains why the integration time noted for some sources was not as ini-

Fig. 3 (a) 3C 277.2 with 0.74'' resolution from the B-configuration data; (b) the northeastern lobe and (c) the southwestern lobe of 3C 277.2 with 0.27'' resolution from the AB combined data (Table 5)

tially planned. For consistency and uniformity with previous works, archive data was recalibrated and remapped using the latest AIPS package. Table 3 provides the observing log that depicts the observing date, total integration time (in seconds), VLA-configuration (A or B) and the bandwidths (in MHz).

To make this paper self-contained, the main steps to reduce the data are briefly reported since they are similar to what is mentioned in F14. For each array, the data has been reduced separately for any given source. IMAGR task from AIPS was used to get all initial maps as described in the AIPS Cookbook. These maps were used as the input into the self-calibration AIPS task CALIB to correct for system phase and amplitude variations (Schwab 1980).

It is to be noted that the input source models in every performed self-calibration incorporated the use of clean com-

ponents (up to the first negative component). The AIPS task CALIB was initiated in phases by using previously obtained images from IMAGR. During the imaging process, the total flux that was cleaned underwent careful scrutiny. If the flux started to decrease, the task IMAGR was stopped. Given the situation that the phase errors became very small (a fraction of a degree) and no improvements in noise were noted, amplitude calibrations were to then performed. Through the use of self-calibration and imaging processes, there was a significant reduction in the map artifacts that resulted due to the phase and amplitude errors. No reweighting was carried out during the A and B data merge.

Table 4 reports the rms noises and the beam sizes for the 8.4 GHz images. As in F14, 88% to 100% of the integrated flux density of the source was recovered. This is following an extrapolation from the radio spectrum of the source us-

Fig. 4 1253+104 with $0.74''$ resolution from the B-configuration data (Table 5)

Fig. 5 (a) 3C 280 with $0.67''$ resolution from the B-configuration data; (b) 3C 280 with $0.21''$ resolution from the AB combined data (Table 5)

ing an online catalog. The percentages of the flux density retrieved from the high-resolution maps are listed in Columns (4) and (9).

Table 5 summarizes for each source the beam size (arc-sec), contour levels intensity (μJy per CLEAN beam area), and peak intensity (mJy/CLEAN beam area) for the available A, B, or AB-configuration. All contours maps are drawn at -1 (dotted lines), 1, 2, 3, 4, 6, 8, 16, 32, 64, 128, 256, 512, and 1024.

3 Sources discussion

3.1 What is a hot spot?

The lack of a singular definition of a HS was addressed by F07, where it was discussed that Laing (1989), Bridle et al. (1994) (hereafter B94), and Leahy et al. (1997) adopted various terminologies to define a HS succinctly. Hardcastle et al. (1997) stated that the lobes of RGs and QSRs very frequently have more than one compact, bright radio feature that meets every utilized hotspot definition. Some of these HSs may be interpreted as jet knots that are representative of

Fig. 6 (a) 3C 280.1 with $0.69''$ resolution from the B-configuration data; (b) 3C 280.1 with $0.54''$ resolution from the AB combined data (Table 5)

internal dissipations in the jet rather than disruption. Some hotspots possess more than two components; however, in the sample of $z < 0.15$, several objects have complicated structures. These structures are either primary (most compact) or secondary (more diffuse) components used for the identification of trends within the hotspot sample structures (Hardcastle et al. 1997).

As in previous works (F02, F07, F12, and F14), we are using the definition of a hotspot as coined by B94. A HS is a structure that must (1) be the brightest feature in the lobe, (2) have a surface brightness that is more than 4 times

greater than that of the surrounding emission, and (3) have a linear FWHM that is less than 5% of the largest diameter of the source. There are additional criteria when a jet is detected. If a jet is detected, the hot spot must then be further from the nucleus than the end of the jet. Following this definition, there can only be one HS per lobe. It is to be noted that B94's criteria of HSs are dependent on angular resolution. However, it is seen that they form a useful basis for classifying HSs at the 8.4 GHz resolution reported.

Fig. 7 (a) 4C 38.35 as a whole; (b) northeastern lobe and (c) southwestern lobe with $0.22''$ resolution from the AB combined data (Table 5)

Fig. 8 (a) 4C 52.27 with $1.20''$ resolution from the B-configuration data; (b) 4C 52.27 with $0.24''$ resolution from the AB combined data (Table 5)

3.2 Sources

(1) **4C 14.11** Hardcastle et al. (1997) presented both low resolution (2.40 arcsec) and high resolution (0.23 arcsec) maps of 4C 14.11 at 8.4 GHz, where several HSs were reported in both lobes. Figure 1(a) is a total intensity contour map at 0.83 arcsec resolution from the B-configuration data only. Multiple features can be observed in both lobes. These features are well resolved at a resolution of 0.21 arcsec from the combined AB data as shown in Fig. 1(b) (northwestern lobe) and 1(c) (southeastern lobe). In the northwestern lobe, features A and B do not fit the definition of a HS as utilized in this study. In the southeastern lobe, several features (C, D, E, and F) were labelled. None of these features fulfills this study's definition of a HS.

(2) **4C 14.27** No core was detected at any frequency in the maps made by Leahy and Perley (1991) or by Goodlet

et al. (2004) for this radio galaxy. Figure 2(a) shows the total intensity image at 0.82 arcsec resolution from the B-configuration data only. There is an asymmetry regarding the lobe's location with respect to the optical identification, shown as a (+) sign on the map, with the southern lobe closer to the optical nucleus than the northern lobe. Figure 2(b) shows the total intensity image at 0.33 arcsec resolution from the combined AB data. No core was detected at this resolution, and no compact features were identified in the two radio lobes to be termed as HSs.

(3) **3C 277.2** The radio source 3C 277.2 is a highly asymmetric double with the closer of the two lobes to the optical identification located to the southwest (Pedelty et al. 1989). This object best shows the radio-optical correlations that are found for nearly all of the galaxies with $z > 0.6$. Observations with ROSAT PSPC (Brunetti et al. 1997) have suggested the presence of hidden quasars to explain the signifi-

cant contribution to the X-ray emission of 3C 277.2 and the great radio-optical alignment (McCarthy et al. 1987). Continuum images also suggested that it is a member of a cluster of galaxies (McCarthy 1988). This is supported by the observation that the asymmetric radio double has one lobe more depolarized than the other, thus indicating the possibility of a confining X-ray halo (Pedelty et al. 1989). Figure 3(a) shows the total intensity image of 3C 277.2 at 0.74 arcsec resolution from the B-configuration data. The detected radio core does not coincide with the optical identification of 3C 277.2 as indicated by the sign (+). Figures 3(b) and 3(c) show the total intensity maps at 0.27 arcsec resolution from the AB combined data for the northeastern and southwestern lobes, respectively. Several features (A, B, C, and d) are observed along the edges of the northeastern lobe. Feature B has the characteristics of an edged HS. In the southwestern lobe, the compact feature E is an edged HS as per the definition employed by this study.

(4) 1253+104 Price et al. (1993) presented a 6 cm map of this quasar showing the overall FR II structure with the northwestern lobe being relatively more pronounced than the southeastern lobe. No A-data at 8.4 GHz exists for this source, so only the low-resolution 0.74 arcsec B-configuration data is presented as shown in Fig. 4. The jet is observed as features C, D, and E. Features A and B mark the outer edges of the northwestern lobe with feature A showing a slight offset from the other features making the jet. The southeastern lobe is resolved as a single bright knot G. At this low-resolution, it was not possible to clearly define the presence of any HS structure in this radio source.

(5) 3C 280 This powerful source is seen to be one of the radio galaxies that have been studied most extensively. The [O II] emission lines of 3C 280 are edge-brightened as revealed in deep optical imaging, and lie along the radio lobes boundaries (Rigler et al. 1992; McCarthy et al. 1995). In soft X-ray energy band, the source is quite faint (Worrall et al. 1994). Figure 5(a) presents the low-resolution 0.67 arcsec B-configuration data. The source is asymmetric with the eastern lobe closer to the weak radio core than the western lobe. It was additionally seen that the eastern lobe is less extended than the western lobe. Figure 5(b) shows the high-resolution 0.21 arcsec from the combined AB data. The eastern lobe is resolved into one large feature A which did not demonstrate a level of compactness that is necessary to be termed as a HS. The western lobe that extends towards the nucleus and northwards was resolved into several features B, C and D. It was seen that feature C has the characteristics of an edged HS.

(6) 3C 280.1 Previous radio maps of this quasar at several wavelengths showed a compact northwestern lobe and a

Fig. 9 4C -06.35 with 0.26'' resolution from the A-configuration data (Table 5)

bright, compact core with a prominent bent jet to the south-east (Akujor et al. 1994; Garrington et al. 1991; Swarup et al. 1982). Figure 6(a) shows the low-resolution 0.69 arcsec B-configuration data. The jet has a clear morphology. The high-resolution AB total intensity map at 0.54 arcsec (Fig. 6(b)) shows that the jet is resolved into several features labeled B through F. The jet is composed of two parts, where the first part is the base (feature F) attached to the radio core G and the second part makes the remaining jet (features E through B). In this second part, the jet appears to change direction several times. In terms of HS, feature B demonstrates sufficient compactness to be termed as a recessed HS. As per the HS definition employed by this study, the northwestern lobe contains no HS.

(7) 4C 38.35 In an early 2.7 GHz radio map, the overall FR II structure of this radio galaxy was depicted (Allington-Smith 1982). Figure 7(a) presents the high-resolution 0.22 arcsec A-configuration data. A radio core is observed close to the optical identification of the source. Figures 7(b) and 7(c) show the total intensity images at the same resolution of the northeastern (NE) and southwestern (SW) lobes, respectively. The NE lobe appeared to have a very faint diffuse emission. In the SW lobe, the features A and B delineate the lobe edges but do not fulfill the requirements of a HS.

Fig. 10 (a) 3C 289 with $0.67''$ resolution from the B-configuration data; (b) 3C 289 with $0.35''$ resolution from the AB combined data (Table 5)

(8) 4C 52.27 Owen and Puschell (1984) reported the detection of a jet in this source using the VLA at 5 GHz. Additionally, Reid et al. (1995) published several maps of 4C 52.27 at 408 MHz, 1.4 and 5 GHz. Figure 8(a) shows the total intensity image at 1.20 arcsec resolution from only the B-configuration data. The source is relatively asymmetric with the southeastern lobe being closer to the radio core than the diffuse and weak northwestern lobe. The jet shows a gentle curvature towards the north as it reaches its terminal point. Figure 8(b) shows the total intensity image at 0.24 arcsec resolution from the AB combined data. The northwestern lobe is resolved at this resolution. The radio core F coincides with the optical identification. The curved jet is resolved into several features A through E. Neither feature A

nor B demonstrated sufficient brightness necessary to fulfill the HS definition as described in this study.

(9) 4C -06.35 Hintzen et al. (1983) presented a 20 cm map that did not clearly depict the structural complexity of the source. However, in the 6 cm map of Price et al. (1993), the complex overall structure of this quasar with bridges connecting the components was well observed. Figure 9 shows the total intensity image at 0.26 arcsec resolution from only the A-configuration data. Several features are labeled (A through D) on the map. It is seen that feature B is clearly a jet structure connecting the radio core C to the northwestern lobe. This lobe is seen to flare up towards the north in a direction which is almost perpendicular to the radio source axis. This lobe also contains a bright fea-

Fig. 11 3C 299 with 0.20'' resolution from the A-configuration data (Table 5)

ture A that satisfies the requirements of an edged HS. The southeastern lobe is composed of two components. The first component is the bright feature D having edged HS characteristics. The second component (feature E) is faint and diffuse and appears to be well detached from this HS.

(10) 3C 289 Liu et al. (1992) described this source as being a remarkably linear, symmetric classical-double structure with hotspots located at the outer edges of the lobes. Optically, 3C 289 showed a central peak of line emission, having a secondary emission region that is a couple of arcsec to the southeast (Best et al. 2000). It was seen to be associated with a faint emission region on the HST image of Best et al. (1997). The low-resolution 0.67 arcsec B-configuration total intensity map (Fig. 10(a)) in this study shows the overall FR II structure of this small radio galaxy. Figure 10(b) shows the total intensity image at 0.35 arcsec resolution from the combined AB data. It is noted that the central radio feature C agrees with the optical identification. The features A and B are representative of the two-edged HSs of this source by our definition.

(11) 3C 299 It was discussed in previous studies that this radio source is well-mapped in the optical (i.e., Privon et al. 2008; McCarthy et al. 1995) and radio regions (i.e., Pearson et al. 1985; Goodlet et al. 2004; Kharb et al. 2008). The source demonstrates asymmetric properties with the northeastern lobe relatively much closer to the central radio core than the southwestern lobe. Figure 11 shows the high-resolution 0.2 arcsec A-configuration total intensity map. The central radio feature C fairly agrees with the optical identification. However, it is noted that the features A and

B in the northeastern and southwestern lobes, respectively, do not fulfill this study's requirements of a HS.

(12) 3C 300 Among all other radio sources selected in this study, 3C 300 was noted to be the largest source in the sample, having a size of 100 arcsecs. The HST NICMOS2 showed that this source is hosted by a compact, elongated ~ 3 kpc elliptical host galaxy with a faint companion located 8 arcsec East and having a slight tidal distortion. From radio observations, the radio axis runs roughly southeast-northwest. Furthermore, it was noted that a faint thread of emission is present along this axis on the northwest side, which is a candidate jet (Floyd et al. 2008). Figure 12(a) shows the total intensity image at 0.75 arcsec resolution from only the B-configuration data. A clear asymmetry regarding the location of the lobes is noted, where it is observed that the southeastern lobe lies closer to the central radio core than the northwestern lobe. In terms of morphology, the southeastern lobe appeared to be more extended than the narrow bridge-like northwestern lobe. Figures 12(b), 12(c) and 12(d) present the total intensity image at 0.25 arcsec resolution from the AB combined data of the southeastern lobe, central radio feature, and northwestern lobe, respectively. The southeastern lobe was resolved into two components, where the first component A fits this study's requirements of an edged HS. The second component B is seen to be a highly diffused feature that makes up the rest of the lobe. As noted in Fig. 12(c), the central radio feature C demonstrates elongation towards the southeastern lobe. To its north, a faint diffuse emission D is noted which may be a jet candidate as mentioned by Floyd et al. (2008). The northwestern lobe (Fig. 12(d)) is seen to be resolved into a highly faint feature E that does not fit this study's definition of a HS.

Fig. 12 (a) 3C 300 with $0.75''$ resolution from the B-configuration data; (b) southeastern lobe, (c) central radio feature, and (d) northwestern lobe of 3C 300 with $0.25''$ resolution from the AB combined data (Table 5)

(13) 4C 20.33 Mantovani et al. (1997) presented two maps of 4C 20.33 at 8.4 and 15 GHz. The 8.4 GHz map stands as a depiction of the long, collimated and highly polarized one-sided jet. At 15 GHz, the polarization was noted to be less for the jet as well as for the northern lobe. Figure 13 shows the total intensity image at 0.24 arcsec resolution from the A-configuration data, as observed in this study. There is no agreement between the optical identification and the central radio feature B. The two radio lobes of this small QSR are seen to be located asymmetrically with respect to the radio core B, with the northern lobe much closer to the radio core than the southern lobe. The southward-running straight jet

is resolved into several features C through G. It is noted that feature H in the southern lobe is merely a jet extension. Features A (in the northern lobe) and I (in the southern lobe) satisfy this study's requirements of edged HSs.

(14) 4C 15.45 In a study by Price et al. (1993), a 5 GHz map of the small quasar 4C 15.45 was presented. The asymmetric nature of this quasar was demonstrated through the relatively closer proximity of the northeastern lobe to the central radio core as compared to the southwestern lobe. The total intensity image at 0.22 arcsec resolution from the A-configuration data is shown in Fig. 14. Several features

Fig. 13 4C 20.33 with 0.24'' resolution from the A-configuration data (Table 5)

Fig. 14 4C 15.45 with 0.22'' resolution from the A-configuration data (Table 5)

A through D are labeled on the map. The southeastern and southwestern lobes are resolved at this resolution as features A and D, respectively. It is additionally noted that feature A demonstrates sufficient compactness to be termed as an edged HS. The jet is resolved into a single feature C. Feature D in the southwestern lobe does not satisfy this study's requirements of a HS.

(15) 4C 13.55 A 5 GHz map of 4C 13.55 was presented by Price et al. (1993), which depicted the overall FR II source structure. Figure 15 shows this study's high-resolution total intensity image at 0.22 arcsec from the A-configuration data. Several radio features A through K are labeled on the map. The two lobes are seen to be asymmetrically located with respect to the radio core C with the northwestern lobe closer to it. The jet is well resolved into several features labeled D through I and shows a gentle curvature on reaching the northwestern lobe. Feature H has sufficient compactness to be termed a recessed HS. The southeastern lobe with its two large features A and B demonstrates less morphological extension than the northwestern lobe. These two features do not fulfill this study's requirement of a HS.

(16) 3C 323 McCarthy et al. (1997) presented a snapshot image of 3C 323 that was taken using the HST Planetary Camera and the F702W filter. The identification was well detected and showed a symmetric structure which was roughly over 1''. A Cambridge 5 km Telescope map of this source made at 11 cm showed the outer lobes as having different structures (Strom et al. 1990). Figure 16 shows this study's high-resolution total intensity image at 0.24 arcsec from the A-configuration data. The northeastern lobe is resolved into a singular component A that shows sufficient

Fig. 15 4C 13.55 with 0.22'' resolution from the A-configuration data (Table 5)

Table 6 Summary of the hot spots for the 12 radio galaxies and 8 quasars

Radio galaxies					Quasars				
Source name (1)	Jet (2)	HS (3)	Location (4)	Jet side (5)	Source name (6)	Jet (7)	HS (8)	Location (9)	Jet side (10)
4C 14.11	–	0	–	–	1253+104	Y	0	–	–
4C 14.27	–	0	–	–	3C 280.1	Y	1	R	Y
3C 277.2	–	2	E	–	4C 52.27	Y	0	–	–
3C 280	Y	1	E	Y	4C –06.35	Y	2	E	Y
4C 38.35	–	0	–	–	4C 20.33	Y	2	E	Y
3C 289	–	2	E	–	4C 15.45	Y	1	E	–
3C 299	–	0	–	–	4C 13.55	Y	1	R	Y
3C 300	–	1	E	–	3C 323.1	Y	1	E	Y
3C 323	Y	2	E	–					
3C 337	–	1	R	–					
3C 340	–	1	E	–					
3C 341	Y	0	–	–					

Notes. The different columns give the following information: (1) and (6) the source name; (2) and (7) if the source has a jet (Y for yes) or no jet (–); (3) and (8) number of hot spots for each source as defined in F02, F07, F12, and F14; (4) and (9) the location of the hot spot as edged (E) or recessed (R); and (5) and (10) if the hot spot is on the jet side (Y for yes) or not (–)

compactness to be termed as an edged HS. The southern part of this source is resolved into several features B (central radio feature) through G. The features labeled C through G are part of a curved jet that marks the western edges of the southern lobe. As per this study's definition of a HS, feature D is noted to be a recessed HS.

(17) 3C 323.1 This source is one of the nearest radio-loud quasars. Pooley and Henbest (1974) showed its triple structure in their 5 GHz map. Several VLA radio maps at different frequencies can be found in the literature (Swarup et al. 1984 at 8.4 GHz; Gower and Hutchings 1984 at 1.4 GHz; Bogers et al. 1994 at 1.4 GHz). The overall FR II radio struc-

Fig. 16 3C 323 with 0.24'' resolution from the A-configuration data (Table 5)

ture was seen to be well observed in these maps. Floyd et al. (2008) used HST NICMOS2 and found that this QSR has a bright nucleus which produces diffraction spikes in the near-infrared image. The H-band image additionally suggested some evidence of disturbances, which may explain the small-scale length fit to the data. It is also possible that the radio emission from this source was Doppler boosted, making it an artificially radio-loud object. The Doppler boosting factors for different sources are calculated by assuming the same intrinsic brightness temperature for each source. There are some extreme sources with the order of 100 that are known as high derived Lorentz factors. Figure 17(a) presents this study's low-resolution total intensity image at 0.84 arcsec from only the B-configuration data. Firstly, the source is seen to be asymmetric with the north-

eastern lobe observed to be in closer proximity to the radio core as compared to the southwestern lobe. Secondly, the jet is easily observed at this resolution in between the central radio core and the southwestern lobe. It is seen that the northeastern lobe does not demonstrate good alignment with the radio source axis that passes through the central radio feature and the jet. Figure 17(b) shows the total intensity image of the northeastern lobe at 0.36 arcsec resolution from the AB combined data. The radio feature A does not demonstrate sufficient compactness to be termed as a HS. Figure 17(c) shows the central radio feature (feature B), the jet (feature C) and the southwestern lobe (features D through G) with the same resolution as in Fig. 17(b). It is noted that feature F at the edges of the southwestern lobe is an edged HS.

(18) 3C 337 Detailed VLA observations of this source at 20, 6 and 2 cm were given by Pedelty et al. (1989). This source is a typical FR II having large asymmetry in both structure and lobe emission. 3C 337 was identified with a $m_R \approx 21$ galaxy in a small cluster group. It was seen that the galaxy contained both nuclear and extended emission-line material. Figure 18(a) presents this study's low-resolution total intensity image at 0.7 arcsec from only the B-configuration data. At this resolution, the eastern lobe shows greater extension than the western lobe. Figures 18(b) and 18(c) show the total intensity image at 0.29 arcsec resolution from the AB combined data of the eastern and western lobes, respectively. The eastern lobe is resolved into two components with the first component containing two radio features A and B. Feature B possesses the characteristic of a recessed HS. The second component C consists of a diffused part along the eastern lobe and shows an inward flare. The western lobe is composed of a tail-like feature D. Additionally, there is a bright feature E at the edges of this lobe. This feature does not demonstrate sufficient compactness to be termed as an edged HS.

(19) 3C 340 McCarthy et al. (1995) presented an emission-line and continuum image of this source. The map showed a relatively elongated continuum that was well-aligned with the radio source axis. Existing literature about this source has incorporated several radio maps of 3C 340. Johnson et al. (1995) presented a weak radio jet candidate extending from the core into the western lobe in their 1.5 GHz map. Best et al. (1997) showed the HS intricacies in their 8.4 GHz VLA A-, B- and C-array map. In an additional study by Mullin et al. (2006), the eastern lobe was shown to be resolved into two peaks in their 0.4 arcsec resolution 5 GHz VLA map. Figure 19(a) presents the total intensity image of 3C 340 at 0.77 arcsec resolution from only the B-configuration data. The two lobes are observed to extend horizontally toward the interior. Figures 19(b) and 19(c)

Fig. 17 (a) 3C 323.1 with 0.84'' resolution from the B-configuration data; (b) northeastern lobe, and (c) central radio feature, the jet, and the southwestern lobe of 3C 323.1 with 0.36'' resolution from the AB combined data (Table 5)

Fig. 18 (a) 3C 337 with $0.70''$ resolution from the B-configuration data; (b) eastern lobe, and (c) western lobe of 3C 337 with $0.29''$ resolution from the AB combined data (Table 5)

show the total intensity image at 0.23 arcsec resolution from the AB combined data of the eastern and western lobes, respectively. The eastern lobe is resolved into several features A through D. The two peaks A and B of the lobe form the lobe's outer edges. It is additionally noted that peak A demonstrates sufficient compactness and brightness to fulfill the criteria of being an edged HS. This lobe shows a westward extension through the fairly narrow bridge C. It is seen

that this lobe subsequently flares up towards the interior. It is unclear if the bridge C is a jet component. The western lobe is resolved into a singular peak that does not present sufficient brightness or compactness to be termed as an edged HS.

(20) 3C 341 Goodlet et al. (2004)'s maps at 1.4 and 5 GHz showed the overall classical double structure with a resolved jet-like structure running into the southwestern lobe. Privon et al. (2008) examined the relationship of the high surface brightness emission-line gas and radio emission of this source and found no alignment between the emission-line nebula and the radio source. The total intensity image of 3C 341 at 0.99 arcsec resolution from only the B-configuration data is shown in Fig. 20(a). The two lobes are seen to be asymmetrically located with respect to the central radio feature, where the southwestern lobe appears to be closer to the central feature. At this resolution, the jet is well observed. Figure 20(b) presents the total intensity image of the northeastern lobe at 0.35 arcsec resolution from the combined AB data. This lobe is resolved into two faint features A and B which do not fulfill the requirements of a HS. At this same resolution, the total intensity image of the southwestern lobe is shown in Fig. 20(c). Several features C (central radio feature) through H are labeled. The straight jet is resolved into several knots (D through G) with feature E being the most compact. The jet is resolved entirely on reaching the southwestern lobe. As per this study's definition, the peak H located at this lobe's outer edges is not a HS.

4 Conclusion

Table 6 summarizes the number of HSs for the 12 RGs and 8 QSRs. Detailed statistical analysis of the final results of the whole sample of 98 FR II sources is deferred to a later paper in this series.

The obtained high-resolution VLA images at 8.4 GHz have provided an unprecedented opportunity to study the morphologies and locations of the HSs in a sample of 12 FR II RGs and 8 FR II QSRs. A wide range of morphologies was observed for these 20 sources. This study was able to identify 10 HSs for the 12 RGs (80% edged and 20% recessed) and 8 HSs for the 8 QSRs (75% edged and 25% recessed). It is seen that the earlier preliminary conclusion of this study still stands, about the fact that RGs possess a greater quantity of edges HSs as compared to the QSRs. Additional findings may be derived about the sources having jets and sources having no HSs. For the jet occurrence, it is concluded that only 3 of the RGs selected in this study have jets as compared to the 8 QSRs having definite jets. For the sources with no HSs based on the B94's definition, it is seen

Fig. 19 (a) 3C 340 with $0.77''$ resolution from the B-configuration data; (b) eastern lobe, and (c) western lobe of 3C 340 with $0.23''$ resolution from the AB combined data (Table 5)

that 5 RGs contained no HSs as compared to only 2 QSRs with no HSs.

In terms of hot spots sizes and linear-size, Hardcastle et al. (1998) find a correlation between the source linear size and hot spot size in a sample of 43 FR II RGs with $z < 0.3$. This may be consistent with Laing (1989) and B94 that the hot spot sizes scale with source linear size. Black (1992), however, finds no such correlation. Kharb et al. (2008) find a correlation between the linear sizes and hot spot sizes in a sample of 13 FR II RGs. This type of correlation is in favor of a hot spot maintaining ram pressure balance as the source propagates through a medium with declining ambient medium (Carvalho and O’Dea 2002). To check this correlation for our sample of 98 sources, we analyzed the hot spot size (geometrical mean) against the core—hot spot distance. We fitted a simple linear model in the log-log space to the RGs data and obtained a slope of 0.17 ± 0.06 . For the QSRs, the linear fit gives a slope of -0.023 ± 0.059 . To further analyze the strength of such correlations between the two physical parameters, we computed the correlation coefficient r (known as Pearson’s r) defined as the ratio of the

covariance of the sample populations to the product of their standard deviations. For the RGs, the correlation coefficient is 0.34. At the 95% level of significance, a critical value of r of 0.232 is listed for a degree of freedom equal to 69. Since our calculated value of r is greater than the critical value, the correlation between the source linear size and HS size is significant. For the 46 QSRs, however, the correlation coefficient is -0.052 . At the 95% level of significance, this is below a critical value of 0.273 given for a degree of freedom of 53 for the QSRs. It can be concluded that our QSR sample does not show a significant correlation between the hot spot size and the source linear size.

In the last paper of this study, thorough statistical and comparative analysis of the quantity of HSs, different morphologies (edged or recessed), and sizes of these HSs for the entire RG and QSR samples will be provided. The investigation of HSs properties in FR II radio sources is essential for a better understanding of source dynamics and their impact on the surrounding environment.

Fig. 20 (a) 3C 341 with 0.99'' resolution from the B-configuration data; (b) northeastern lobe, and (c) southwestern lobe of 3C 341 with 0.35'' resolution from the AB data (Table 5)

Acknowledgements This study owes its thanks to the NRAO AIPS group for the software used in the data reduction and analysis. NASA/IPAC Extragalactic Database was used, which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration. Thanks are also addressed to the anonymous referee for his valuable comments to improve the reading and quality of this paper.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

commons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Akujor, C.E., Lüdke, E., Browne, I.W., et al.: *Astron. Astrophys. Suppl. Ser.* **105**, 247 (1994)
- Allington-Smith, J.R.: *Mon. Not. R. Astron. Soc.* **199**, 611 (1982)
- Allington-Smith, J.R., Perryman, M.A.C., Longair, M.S.: *Mon. Not. R. Astron. Soc.* **201**, 311 (1982)

- Allington-Smith, J.R., Lilly, S.J., Longair, M.S.: *Mon. Not. R. Astron. Soc.* **213**, 243 (1985)
- Barthel, P.D.: *Astrophys. J.* **336**, 606 (1989)
- Becker, R.H., White, R.L., Edwards, A.L.: *Astrophys. J. Suppl. Ser.* **75**, 1 (1991)
- Best, P.N., Longair, M.S., Röttgering, H.J.A.: *Mon. Not. R. Astron. Soc.* **292**, 758 (1997)
- Best, P.N., Röttgering, H.J.A., Longair, M.S.: *Mon. Not. R. Astron. Soc.* **311**, 1 (2000)
- Binette, L., Carignan, C., Bolton, J.G., Wright, A.E.: *Aust. J. Phys.* **34**, 407 (1981)
- Black, A.R.S.: Ph.D. thesis. Univ. Cambridge (1992)
- Blandford, R.D., Rees, M.J.: *Mon. Not. R. Astron. Soc.* **169**, 395 (1974)
- Bogers, W.J., Hes, R., Barthel, P.D., Zensus, J.A.: *Astron. Astrophys. Suppl. Ser.* **105**, 91 (1994)
- Bridle, A.H., Perley, R.A.: *Annu. Rev. Astron. Astrophys.* **22**, 319 (1984)
- Bridle, A.H., Hough, D.H., Lonsdale, C.J., et al.: *Astrophys. J.* **108**, 766 (1994). B94
- Brunetti, G., Setti, G., Comastri, A.: *Astron. Astrophys.* **325**, 898 (1997)
- Carvalho, J.C., O'Dea, C.P.: *Astrophys. J. Suppl. Ser.* **141**, 371 (2002)
- Dixon, R.S.: *Astrophys. J. Suppl. Ser.* **20**, 1 (1970)
- Fanaroff, B.L., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **167**, 31P (1974)
- Fernini, I.: *Astron. J.* **123**, 132 (2002). F02
- Fernini, I.: *Astron. J.* **134**, 158 (2007). F07
- Fernini, I.: *Afr. Skies* **16**, 56 (2012). F12
- Fernini, I.: *Astrophys. J. Suppl. Ser.* **212**, 19 (2014). F14
- Floyd, D.J.E., Axon, D., Baum, S., et al.: *Astrophys. J. Suppl. Ser.* **177**, 148 (2008)
- Garrington, S.T., Conway, R.G., Leahy, J.P.: *Mon. Not. R. Astron. Soc.* **250**, 171 (1991)
- Gilbert, G.M., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **309**, 681 (1999)
- Gilbert, G.M., Riley, J.M., Hardcastle, M.J., et al.: *Mon. Not. R. Astron. Soc.* **351**, 845 (2004)
- Goodlet, J.A., Kaiser, C.R., Best, P.N., Dennett-Thorpe, J.: *Mon. Not. R. Astron. Soc.* **347**, 508 (2004)
- Gower, A.C., Hutchings, J.B.: *Astron. J.* **89**, 1658 (1984)
- Gregorini, L., Padrielli, L., Parm, P., Gilmore, G.: *Astron. Astrophys. Suppl. Ser.* **74**, 107 (1988)
- Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **288**, 859 (1997)
- Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **296**, 445 (1998)
- Hintzen, P., Ulvestad, J., Owen, F.: *Astron. J.* **88**, 709 (1983)
- Hutchings, J.B., Price, R., Gower, A.C.: *Astrophys. J.* **329**, 122 (1988)
- Ishwara-Chandra, C.H., Saikia, D.J.: *Mon. Not. R. Astron. Soc.* **309**, 100 (1999)
- Jenkins, C.R., Pooley, G.G., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **84**, 61 (1977)
- Johnson, R.A., Leahy, J.P., Garrington, S.T.: *Mon. Not. R. Astron. Soc.* **273**, 877 (1995)
- Katgert-Merkelijn, J., Lari, C., Padrielli, L.: *Astron. Astrophys. Suppl. Ser.* **40**, 91 (1980)
- Kellerman, K.I., Pauliny-Toth, I.I.K., Williams, P.J.S.: *Astrophys. J.* **157**, 1 (1969)
- Kharb, P., O'Dea, C.P., Baum, S.A., et al.: *Astrophys. J. Suppl. Ser.* **174**, 74 (2008)
- Kristian, J., Sandage, A., Westphal, J.: *Astrophys. J.* **221**, 383 (1978)
- Laing, R.A.: *Mon. Not. R. Astron. Soc.* **193**, 427 (1981)
- Laing, R.A.: In: Meisenheimer, K., Röser, H.-J. (eds.) *Hot Spots in Extragalactic Radio Sources*, p. 27. Springer, Berlin (1989)
- Laing, R.A., Riley, J.M., Longair, M.S.: *Mon. Not. R. Astron. Soc.* **204**, 151 (1983)
- Leahy, J.P., Perley, R.A.: *Astron. J.* **102**, 537L (1991)
- Leahy, J.P., Williams, A.G.: *Mon. Not. R. Astron. Soc.* **210**, 929 (1984)
- Leahy, J.P., Black, A.R.S., Dennett-Thorpe, J., et al.: *Mon. Not. R. Astron. Soc.* **291**, 20 (1997)
- Liu, R., Pooley, G., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **257**, 545 (1992)
- Lyne, A.G.: *Mon. Not. R. Astron. Soc.* **158**, 431 (1972)
- Mantovani, F., Junor, W., Fanti, R., et al.: *Astron. Astrophys. Suppl. Ser.* **125**, 573 (1997)
- McCarthy, P.J.: Ph.D. thesis. Univ. California (1988)
- McCarthy, P.J., van Breugel, W.J.M., Spinrad, H., Djorgovski, S.: *Astrophys. J.* **321**, L29 (1987)
- McCarthy, P.J., Spinrad, H., van Breugel, W.J.M.: *Astrophys. J. Suppl. Ser.* **99**, 27 (1995)
- McCarthy, P.J., Miley, G.K., de Koff, S., et al.: *Astrophys. J. Suppl. Ser.* **112**, 415 (1997)
- Meisenheimer, K., Röser, H.J., Hiltner, P.R., Yates, M.G., et al.: *Astron. Astrophys.* **219**, 63–86 (1989)
- Mullin, L.M., Hardcastle, M.J., Riley, J.M.: *Mon. Not. R. Astron. Soc.* **372**, 113 (2006)
- Nilsson, K., Valtonen, M.J., Kotilainen, J., Jaakkola, T.: *Astrophys. J.* **413**, 453 (1993)
- Owen, F.N., Puschell, J.J.: *Astron. J.* **89**, 932 (1984)
- Peacock, J.A., Wall, J.V.: *Mon. Not. R. Astron. Soc.* **198**, 843 (1982)
- Pearson, T.J., Perley, R.A., Readhead, A.C.S.: *Astron. J.* **90**, 378 (1985)
- Pedetty, J.A., Rudnick, L., McCarthy, P.J., Spinrad, H.: *Astron. J.* **97**, 647 (1989)
- Perryman, M.A.C., Lilly, S.J., Longair, M.S., Downes, A.J.B.: *Mon. Not. R. Astron. Soc.* **209**, 159 (1984)
- Pooley, G.G., Henbest, S.N.: *Mon. Not. R. Astron. Soc.* **169**, 477 (1974)
- Price, R., Gower, A.C., Hutchings, J.B., et al.: *Astrophys. J. Suppl. Ser.* **86**, 365 (1993)
- Privon, G.C., O'Dea, C.P., Baum, S.A., et al.: *Astrophys. J. Suppl. Ser.* **175**, 423 (2008)
- Reid, A., Shone, D.L., Akujor, C.E., et al.: *Astron. Astrophys. Suppl. Ser.* **110**, 213 (1995)
- Rigler, M., Lilly, S., Stockton, A., Hammer, F., Le Fèvre, O.: *Astrophys. J.* **385**, 61 (1992)
- Riley, J.M., Pooley, G.G.: *Mon. Not. R. Astron. Soc.* **80**, 105 (1975)
- Saikia, D.J., Kulkarni, V.K., Porcas, R.W.: *Mon. Not. R. Astron. Soc.* **219**, 719 (1986)
- Schwab, F.R.: *Proc. SPIE* **231**, 18 (1980)
- Spinrad, H., Djorgovski, S., Marr, J., Aquilar, L.: *Publ. Astron. Soc. Pac.* **97**, 932 (1985)
- Strom, R.G., Conway, R.G.: *Astron. Astrophys. Suppl. Ser.* **61**, 547 (1985)
- Strom, R.G., Riley, J.M., Spinrad, H., et al.: *Astron. Astrophys.* **227**, 19 (1990)
- Swarup, G., et al.: *Mon. Not. R. Astron. Soc.* **201**, 393 (1982)
- Swarup, G., Sinha, R.P., Hildrup, K.: *Mon. Not. R. Astron. Soc.* **208**, 813 (1984)
- Wills, D., Lynds, R.: *Astrophys. J. Suppl. Ser.* **36**, 317 (1978)
- Worrall, D.M., Lawrence, C.R., Pearson, T.J., Readhead, A.C.S.: *Astrophys. J.* **420L**, 17 (1994)