Hot spots analysis of a sample of 98 Fanaroff-Riley II radio sources

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Abstract. This paper reports our final results related to the study of hot spots (HSs) in a sample of 98 Fanaroff-Riley class II (FR II) radio sources using the VLA at 8.4 GHz. The sample contains 52 radio galaxies (RGs) and 46 quasars (QSRs). We discuss the properties of these HSs, i.e., location (edged or recessed), morphology, and size. The main result is that the number of edged (and recessed) HSs is more for the RGs than for the QSRs. Regarding the compactness of these HSs, QSRs tend to have more compact HSs than RGs. We also found a significant correlation between the hot spot size and the source linear size for the RGs, but not for the QSRs. We discuss the overall properties of the HSs in light of the current models of radio sources.

Keywords: galaxies: active – galaxies: jets

1. Introduction

This paper is the last paper of a series that reports on the analysis of hot spots in classical double radio sources, or FR II sources [1]. In previous works ([2], [3], [4], [5], and [6]; hereafter F02, F07, F12, F14, and F18), we have presented the VLA images at 8.4 GHz and partial analysis of a 98 FR II sources (52 radio galaxies [RGs] and 46 quasars [QSRs]). We have shown that with the availability of high-resolution radio observations, that HSs are not always located at the outer edges of the radio lobes (i.e., edged hot spot), but sometimes well embedded inside them (i.e., recessed hot spot). Several definitions of a hot spot exist ([7]; [8], hereafter B94; [9] in terms of its brightness, physical size, and location. For simplicity, the B94’s definition of a hot spot was uniformly applied to all of our sources. B94’s HS definition allows for only one HS per lobe.

The primary aim of this study was to obtain the highest possible dynamic range and angular resolution using the VLA at 8.4 GHz. This has allowed us to detect low surface brightness emission yet still distinguish jets from other features such as hot spots in our 98 radio sources.

In F12, F14, and F18, we briefly discussed the importance of the location of a hot spot within the radio lobe as related to the validity of the underlying models of radio sources in which hot spots are always edged. The study of hot spots and their location (edged or recessed) is beneficial to make a comparative study of RGs and QSRs and to better understand the different models of radio sources, i.e.,
the unification scheme of Barthel [10]. For the 98 FR IIs (52 RGs and 46 QSRs) discussed in F02, F07, F12, F14, and F18, we were able to identify 129 HSs (89 edged and 40 recessed). For the 46 QSRs (39 with definite jets), we have identified 58 HSs with 19 recessed and 39 edged. For the 52 RGs (only 12 with definite jets), 71 HSs were identified with 21 recessed and 50 edged. Overall, we have found that the 98 sources have more edged hot spots than recessed and that there is a tendency for the RGs to have more edged (and recessed) HSs than the QSRs.

In Section 2, we briefly describe our sample selection criteria of the 52 RGs and 46 QSRs sources. Section 3 presents our HSs statistical analysis. In Section 4, we summarize the main results. Throughout this paper, we use $H_0 = 75 \text{ km} \cdot \text{s}^{-1} \text{Mpc}^{-1}$, $q_0 = 0.5$, and we assume a Friedmann-Robertson cosmology.

2. The data

2.1. Sample and Observations

Our large sample of 98 FR II radio sources has been mainly drawn from the sample of Nilsson et al. [11] that includes 540 radio sources (267 radio galaxies and 273 quasars) with well-known FR II morphologies. The selection criteria are fully described in the previous works (F02, F07, F12, F14 and F18), so we briefly list them here: (a) declination: $-15^\circ \leq \delta \leq 80^\circ$; (b) redshift: $0.1 < z < 2.0$; (c) integrated flux density: $S_{178 \text{ MHz}} > 5 \text{ Jy}$; and (d) source largest angular size (SLAS): $9^\circ \leq \text{SLAS} \leq 100^\circ$.

Table 1 and Table 2 list the basic radio properties of all the RGs and QSRs, respectively.

| IAU Name | 3C Name | $z$ | SLAS (arcsec) | L (kpc) | $S_{5 \text{ cm}}$ (Jy) | Ref. |
|----------|---------|----|--------------|--------|----------------|-----|
| 0013+79  | 3C 6.1  | 0.840 | 26 | 144.1 | 1.04 | F14 |
| 0031+391 | 3C 13   | 1.351 | 32.5 | 186.6 | 0.40 | F14 |
| 0038+32  | 3C 19   | 0.482 | 9.6 | 44.9 | 1.26 | F14 |
| 0040+517 | 3C 20   | 0.174 | 51 | 130 | 4.18 | F12 |
| 0107+315 | 3C 34   | 0.689 | 48 | 254.2 | 0.43 | F12 |
| 0123+329 | 3C 41   | 0.794 | 27.2 | 149.1 | 1.46 | F14 |
| 0125+287 | 3C 42   | 0.395 | 28 | 119.4 | 0.84 | F02 |
| 0154+286 | 3C 55   | 0.7348 | 69 | 371.6 | 0.88 | F12 |
| 0220+397 | 3C 65   | 1.176 | 20 | 114.9 | 0.77 | F14 |
| 0231+313 | 3C 68.2 | 1.575 | 22.3 | 126.6 | 0.18 | F14 |
| 0411+14  | 4C 14.11 | 0.206 | 88 | 253.1 | 0.89 | F18 |
| 0433+293 | 3C 123  | 0.218 | 41.1 | 123 | 16.32 | F14 |
| 0453+224 | 3C 132  | 0.214 | 22.3 | 65.9 | 1.05 | F14 |
| 0605+448 | 3C 153  | 0.277 | 9.26 | 32.4 | 1.35 | F14 |
| 0702+74  | 3C 173.1| 0.292 | 61 | 220.2 | 0.77 | F14 |
| 0806+42  | 3C 194  | 1.184 | 14.2 | 81.6 | 0.61 | F14 |
| 0818+472 | 3C 197.1| 0.130 | 14 | 28.5 | 0.86 | F14 |
| 0824+294 | 3C 200  | 0.458 | 27.3 | 182 | 0.66 | F14 |
| 0832+14  | 4C 14.27| 0.392 | 38 | 161.4 | 0.302 | F18 |
| 0905+380 | 3C 217  | 0.8975 | 12 | 67.2 | 0.48 | F14 |
| 0927+362 | 3C 220.1| 0.62 | 30 | 154 | 0.54 | F14 |
| 0947+14  | 3C 228  | 0.552 | 47.2 | 232.8 | 1.14 | F14 |
| 1008+467 | 3C 239  | 1.781 | 11.2 | 62.6 | 0.33 | F14 |
| 1009+745 | 4C 74.16| 0.568 | 40 | 199.3 | 0.75 | F14 |
| 1030+585 | 3C 244.1| 0.428 | 51 | 226.1 | 1.12 | F02 |
| 1056+432 | 3C 247  | 0.7489 | 13 | 70.3 | 0.95 | F14 |
| 1108+359 | 3C 252  | 1.1035 | 57 | 326.5 | 0.32 | F12 |
| IAU Name     | 3C Name | z    | SLAS (arcsec) | L (kpc) | S5GHz (Jy) | Ref. |
|-------------|---------|------|---------------|---------|------------|------|
| 0017+154    | 3C 9    | 2.012| 14            | 76.4    | 0.49       | F02  |
| 0033+183    | 3C 14   | 1.469| 26            | 148.6   | 0.61       | F14  |
| 0038-019    | 4C -02.04 | 1.690| 20            | 112.6   | 0.42       | F14  |
| 0048+509    | 3C 22   | 0.937| 24            | 135.3   | 0.76       | F12  |
| 0229+341    | 3C 68.1 | 1.238| 53            | 304.6   | 0.78       | F12  |
| 0307+169    | 3C 79   | 0.255| 88.7          | 294.4   | 1.31       | F14  |
| 0710+118    | 3C 175  | 0.768| 52            | 283     | 0.69       | F07  |
| 0723+679    | 3C 179  | 0.846| 15            | 83.2    | 0.90       | F14  |
| 0821+447    | 4C 44.17| 0.904| 26            | 145.9   | 0.24       | F14  |
| 0833+654    | 3C 204  | 1.112| 37            | 212     | 0.37       | F07  |
| 0835+580    | 3C 205  | 1.534| 16            | 91.1    | 0.67       | F14  |
| 0838+133    | 3C 207  | 0.684| 14            | 74      | 1.44       | F14  |
| 0839+616    | 4C 61.19| 0.862| 26            | 144.7   | 0.23       | F14  |
| 0850+140    | 3C 208  | 1.11 | 14            | 80.2    | 0.56       | F02  |
| 0855+143    | 3C 212  | 1.049| 9             | 51.4    | 0.89       | F14  |
| 0903+169    | 3C 215  | 0.411| 60            | 261     | 0.43       | F07  |
| 0906+430    | 3C 216  | 0.67 | 30            | 157.6   | 1.81       | F14  |
| 0941+100    | 3C 226  | 0.817| 35            | 192.9   | 0.64       | F14  |
| 0957+003    | 4C 00.34| 0.907| 31.4          | 176.2   | 0.36       | F14  |
| 1100+772    | 3C 249.1| 0.311| 53            | 198.6   | 0.8        | F07  |
| 1103-006    | 4C -00.43| 0.428| 21            | 93.1    | 0.54       | F14  |
The 98 sources were observed using the VLA at 8.4 GHz in its A and B configuration. A large number of our sources had previous VLA observations, so the VLA archive was extensively used. For consistency and uniformity with all of our previous works, each source has been recalibrated and remapped using the latest AIPS package. The data calibration and reduction’s details are given in F02, F07, F12, F14, and F18.

2.2. Comparison of the RG and QSR Samples
The 52 RGs have angular sizes ranging from 9.26" (3C 153) to 100" (3C 300), redshifts from 0.13 (3C 197.1) to 1.781 (3C 239) and flux densities at 5 GHz from 0.18 Jy (3C 68.2) to 16.32 Jy (3C 123). The average values for the angular size, redshift, and flux density are 37.6", 0.70, and 1.22 Jy, respectively. For the 46 QSRs, the angular sizes are from 9" (3C 212) to 88.7" (3C 79), the redshifts from 0.255 (3C 79) to 2.012 (3C 9), and the flux densities at 5 GHz from 0.07 Jy (2209+152) to 1.81 Jy (3C 216), with average values of 27.22", 0.9425, and 0.65 Jy, respectively. Figures 1 and 2 show the normalized histograms for the redshift (z) and the source largest angular size (SLAS) for the 52 RGs and 46 QSRs.
Figure 1. – Distribution of the redshift for the 98 observed radio sources using an interval width of 0.2.

Figure 2. – Distribution of the source largest angular size (SLAS, in arcsec) for the whole sample. An interval width bin of 10 arcsec was used.

3. Hot Spots Analysis

3.1. Edged and recessed hot spots
We have identified a total of 129 hot spots (HSs) for the 98 observed sources (52 RGs and 46 QSRS). From the model point of view of FR II radio sources, each FR II source is supposed to have two HSs,
so the occurrence percentage rate of HSs has to be 100%, i.e., two HS per FR II object. However, for the 98 observed sources, the overall occurrence percentage rate of HSs was found to be only 66%. For the 52 RGs, the occurrence percentage rate is 68% with the identification of 71 HSs (70% and 30% are edged and recessed, respectively). For the 46 QSRs, the occurrence percentage rate is 63% with the identification of 58 HSs (67% and 33% are edged and recessed, respectively). We ran the Student’s t-test to compare the distributions of the numbers of HSs in both the RGs and the QSRs. We find a probability of 0.401 indicating that the distributions of the number of HSs are similar between the RGs and QSRs.

For the 52 RGs, there are 51 edged and 20 recessed HSs. For the 46 QSRs, we have 39 edged, and 19 recessed HSs. Figure 3 presents a normalized distribution of the number of HSs as edged or recessed for each type of source. A preliminary conclusion for the 98 observed sources is that the RGs have more edged (and recessed) hot spots than the QSRs.

![Normalized Number of HSs](image)

**Figure 3.** Distribution of the normalized number of HSs as edged or recessed for the RGs and QSRs.

### 3.2. Hot spots sizes

The distributions of the HS sizes, hot spot largest angular size (HSLAS) and hot spot smallest angular size (HSSAS) obtained using the AIPS task JMFIT, are reported in Tables 3 & 4 for the RGs and QSRs, respectively. The HSLAS and HSSAS are the major and minor axes of a fitted elliptical Gaussian component, respectively. We need to note that such fitting does not always represent the hot spots well. Our definition of a hot spot has its difficulties, so we applied the fitting method as follows: the Gaussian fitting routine was run a number of different times on slightly different regions or with slightly different initial guesses. In most of the sources, these fittings gave the same results, and this is reported in Tables 3 & 4 as averages.

The distribution of the hot spot size using the geometrical mean of the largest and smallest angular sizes is shown in Figure 4. For the RGs, the mean of the geometrical mean is 0.469. If we choose a confidence coefficient of 95%, a margin of error of 0.04 is computed. Thus, we are 95% confident that the population mean is between 0.429 and 0.509. For the QSRs, the mean of the geometrical mean is 0.408. With the same confidence coefficient of 95%, the margin of error is 0.03. This gives a 95% confidence that the population mean is in between 0.378 and 0.438. We should note that the margin of
errors reported here and elsewhere are calculated using the population standard deviation (sample standard deviation) divided by the square root of the sample size and multiplied by the confidence coefficient of 1.96. From this analysis of the geometrical mean, it can be preliminary concluded that the HSs in QSRs are more compact than those in the RGs.

To further check on the above conclusion, we ran two tests. A Kolmogorov-Smirnov (KS) two-sample test shows that the maximum difference between the cumulative distributions, $D$, is 0.2674 with a corresponding $P$-value of 0.017. The $P$-value number reports if the numbers differ significantly. As usual, the null hypothesis is rejected if $P$ is "small." A Student’s T-test gives a probability, assuming the null hypothesis, of 0.020, which is less than the standard critical value of 0.05 (5%). The two types of objects have different HSs compactness.

Table 3. Hot Spots Properties for the 52 Radio Galaxies.

| Source Name (1) | Lobe (2) | Feature (3) | Location (4) | Peak $S_{8.4\,\text{GHz}}$ (mJy/beam) (5) | Integr. $S_{8.4\,\text{GHz}}$ (mJy/beam) (6) | HSLAS (arcsec) (7) | HSSAS (arcsec) (8) | Jet Side (9) |
|-----------------|----------|-------------|--------------|------------------------------------------|--------------------------------------------|------------------|------------------|-------------|
| 3C 6.1          | NE       | A           | Edged        | 63.0                                      | 289.6                                      | 0.78             | 0.50             | No          |
|                 | SW       | E           | Edged        | 27.6                                      | 104                                         | 0.64             | 0.50             | No          |
| 3C 13           | SE       | A           | Edged        | 23.5                                      | 33.6                                       | 0.41             | 0.36             | No          |
|                 | NW       | D           | Edged        | 65.9                                      | 110.7                                      | 0.45             | 0.35             | No          |
| 3C 19           | NE       | A           | Edged        | 127.5                                     | 323                                        | 0.50             | 0.37             | No          |
|                 | SW       | F           | Edged        | 51.2                                      | 128                                        | 0.51             | 0.36             | No          |
| 3C 20           | SE       | C           | Recessed     | 47                                        | 76                                         | 0.33             | 0.31             | No          |
|                 | NW       | F           | Recessed     | 95                                        | 199                                        | 0.38             | 0.35             | No          |
| 3C 34           | --       | --          | --           | --                                        | --                                         | --               | --               | --          |
| 3C 41           | SE       | A           | Edged        | 47.7                                      | 194.1                                      | 0.6              | 0.40             | Yes         |
|                 | NW       | L           | Edged        | 11                                        | 42.8                                       | 0.61             | 0.36             | No          |
| 3C 42           | NW       | N           | Edged        | 52.2                                      | 146.3                                      | 1.08             | 0.62             | No          |
| 3C 55           | E        | A           | Edged        | 17.1                                      | 56.1                                       | 0.7              | 0.58             | No          |
|                 | W        | J           | Edged        | 45.0                                      | 62.0                                       | 0.45             | 0.37             | No          |
| 3C 65           | E        | B           | Recessed     | 15.1                                      | 38.2                                       | 0.57             | 0.46             | No          |
|                 | W        | G           | Edged        | 39.8                                      | 151                                        | 0.71             | 0.54             | No          |
| 3C 68.2         | SE       | B1          | Recessed     | 1.9                                       | 4.3                                        | 0.53             | 0.44             | No          |
|                 | NW       | D           | Recessed     | 2.7                                       | 7.9                                        | 0.57             | 0.53             | No          |
| 4C 14.11        | --       | --          | --           | --                                        | --                                         | --               | --               | --          |
| 3C 123          | SE       | B           | Recessed     | 185                                       | 503                                        | 0.59             | 0.39             | No          |
|                 | NW       | D           | Recessed     | 14                                        | 18                                         | 0.35             | 0.31             | No          |
| 3C 132          | SE       | A           | Edged        | 12.5                                      | 49.3                                       | 0.6              | 0.52             | No          |
|                 | NW       | F           | Edged        | 39.6                                      | 62.6                                       | 0.36             | 0.35             | No          |
| 3C 153          | NE       | D           | Recessed     | 77.2                                      | 94.9                                       | 0.31             | 0.31             | No          |
|                 | SW       | B           | Edged        | 106.9                                     | 220.5                                      | 0.45             | 0.36             | No          |
| 3C 173.1 | NE | C | Edged | 3.1 | 6.4 | 0.59 | 0.38 | No |
| 3C 194 | SE | A | Edged | 61.6 | 104 | 0.28 | 0.24 | No |
| 3C 197.1 | S | A | Edged | 3.1 | 18.2 | 1.1 | 0.75 | No |
| 3C 200 | SE | C | Recessed | 4.7 | 11.2 | 0.86 | 0.67 | Yes |
| 4C 14.27 | -- | -- | -- | -- | -- | -- | -- | -- |
| 3C 217 | NW | G | Edged | 22.2 | 32.7 | 0.40 | 0.36 | No |
| 3C 220.1 | E | D | Edged | 5.54 | 16.4 | 0.51 | 0.33 | Yes |
| 3C 228 | S | A | Edged | 136 | 243 | 0.55 | 0.38 | Yes |
| 3C 239 | E | A | Recessed | 23.8 | 44.1 | 0.41 | 0.33 | No |
| 4C 74.16 | NE | A | Recessed | 1.4 | 8.0 | 0.6 | 0.51 | No |
| 3C 244.1 | S | D | Recessed | 19.7 | 21.3 | 0.31 | 0.31 | No |
| 3C 247 | NE | A | Edged | 239 | 355 | 0.53 | 0.5 | No |
| 3C 252 | SE | C | Edged | 2.6 | 31 | 0.27 | 0.23 | No |
| 3C 265 | NW | I | Edged | 1.95 | 18.8 | 1.29 | 0.87 | No |
| 3C 267 | NE | A | Edged | 10.1 | 20 | 0.32 | 0.30 | No |
| 3C 268.1 | E | B | Recessed | 8.7 | 16.7 | 0.33 | 0.25 | No |
| 3C 277.2 | SW | E | Edged | 45.1 | 86.1 | 0.40 | 0.34 | No |
| 3C 280 | W | C | Edged | 300 | 500 | 0.29 | 0.25 | No |
| 4C 38.35 | -- | -- | -- | -- | -- | -- | -- | -- |
| 3C 289 | SE | A | Edged | 100 | 136.2 | 0.42 | 0.4 | No |
| Source Name | Lobe | Feature | Location | Peak $S_{8.4\,\text{GHz}}$ (mJy/beam) (5) | Integr. $S_{8.4\,\text{GHz}}$ (mJy/beam) (6) | HSLAS (arcsec) (7) | HSSAS (arcsec) (8) | Jet Side (9) |
|-------------|------|---------|----------|------------------------------------------|-----------------------------------------------|------------------|------------------|--------------|
| 3C 9        | NW   | A       | Edged    | 6.0                                        | 22.4                                          | 0.68             | 0.53             | No           |
|             | SE   | N       | Edged    | 1.8                                        | 4.83                                          | 0.6              | 0.43             | Yes          |
| 3C 14       | SE   | B       | Recessed | 21.9                                       | 41.6                                          | 0.44             | 0.39             | Yes          |

Notes: Col. (1) gives the source name. Col. (2) specifies the side of the source where the hot spot is located. Col. (3) lists the features which have been described as hot spots in the radio maps. Col. (4) indicates if the HS is edged or recessed. Cols. (5) and (6) give the peak and integrated flux densities at 8.4 GHz. Cols. (7) and (8) give the hot spot largest angular (HSLAS) and the smallest angular size (HSSAS), which are the major and minor axes of a fitted elliptical Gaussian component. Col. (9) reports if the hot spot is on the jetted side.

Table 4. Hot Spots Properties for the 46 Radio Galaxies.
| Location | Orientation | Type | Width | Height | Depth | Taper | Edged | Recessed | Status |
|----------|-------------|------|-------|--------|-------|-------|-------|----------|--------|
| 4C-02.04 | N           | A    | Recessed | 7.9    | 23.3  | 0.44  | 0.38  | No       |        |
|          | S           | J    | Recessed | 3.2    | 8.7   | 0.42  | 0.37  | Yes      |        |
| 3C 22    | SE          | A    | Edged    | 43.4   | 126.3 | 0.51  | 0.36  | No       |        |
|          | NW          | D    | Edged    | 93.5   | 124   | 0.30  | 0.28  | Yes      |        |
| 3C 68.1  | N           | A    | Edged    | 51.2   | 126.4 | 0.48  | 0.27  | Yes      |        |
| 3C 79    | E           | A    | Edged    | 1.94   | 9.1   | 0.61  | 0.34  | No       |        |
|          | W           | K    | Recessed | 2.7    | 5.1   | 0.37  | 0.23  | No       |        |
| 3C 175   | NE          | B    | Edged    | 39.2   | 111.3 | 0.58  | 0.47  | No       |        |
|          | SW          | N    | Recessed | 16.3   | 50.8  | 0.65  | 0.46  | Yes      |        |
| 3C 179   | E           | A    | Edged    | 5.5    | 33    | 0.74  | 0.6   | No       |        |
|          | W           | H    | Edged    | 22.7   | 40.8  | 0.38  | 0.35  | Yes      |        |
| 4C 44.17 | SE          | A    | Edged    | 11.9   | 25.7  | 0.36  | 0.32  | No       |        |
| 3C 204   | E           | A    | Edged    | 35.8   | 64.9  | 0.32  | 0.3   | No       |        |
|          | W           | I    | Recessed | 57.4   | 103.8 | 0.33  | 0.3   | Yes      |        |
| 3C 205   | N           | A    | Edged    | 19.3   | 37.4  | 0.43  | 0.38  | No       |        |
|          | S           | D    | Recessed | 77.1   | 92.2  | 0.34  | 0.30  | Yes      |        |
| 3C 207   | E           | A    | Edged    | 10.6   | 52.4  | 0.50  | 0.44  | Yes      |        |
| 4C 61.19 | NW          | H    | Edged    | 22.3   | 76.5  | 0.49  | 0.34  | Yes      |        |
| 3C 208   | W           | K    | Recessed | 8.2    | 17.4  | 0.41  | 0.3   | Yes      |        |
|          | E           | A    | Edged    | 44     | 95.4  | 0.37  | 0.34  | No       |        |
| 3C 212   | SE          | A    | Edged    | 49.3   | 137.8 | 0.43  | 0.41  | No       |        |
|          | NW          | J    | Edged    | 24.4   | 39    | 0.35  | 0.29  | Yes      |        |
| 3C 215   | SE          | B    | Recessed | 2.12   | 5.94  | 0.56  | 0.45  | Yes      |        |
| 3C 216   | NE          | A    | Edged    | 95.7   | 228.1 | 0.48  | 0.39  | No       |        |
|          | SW          | C    | Recessed | 22.4   | 34.8  | 0.38  | 0.32  | No       |        |
| 3C 226   | SE          | A    | Edged    | 29.7   | 50.6  | 0.33  | 0.3   | No       |        |
|          | NW          | D    | Recessed | 3.05   | 8.15  | 0.42  | 0.37  | No       |        |
| 4C 00.34 | NW          | F    | Recessed | 3.8    | 15    | 0.72  | 0.34  | Yes      |        |
| 3C 249.1 | E           | A    | Edged    | 27.6   | 56.8  | 0.5   | 0.4   | Yes      |        |
| 4C-00.43 | NW          | K    | Edged    | 4      | 8.6   | 0.37  | 0.33  | Yes      |        |
| 1136-135 | NW          | I    | Edged    | 58.1   | 114.9 | 0.46  | 0.45  | Yes      |        |
| 3C 263   | SE          | A    | Edged    | 183.3  | 310   | 0.4   | 0.38  | Yes      |        |
|          | NW          | F    | Recessed | 6.53   | 15.3  | 0.48  | 0.44  | No       |        |
| 4C 49.22 | S           | L    | Edged    | 2.3    | 7.3   | 0.39  | 0.35  | Yes      |        |
| Object | Orientation | Type | Edged | Edged | 12.4 | 30 | 0.40 | 0.30 | No | Yes |
|--------|-------------|------|-------|-------|------|----|------|------|----|-----|
| 3C 268.4 | NE SW | A F | Edged | Edged | 12.4 | 30 | 0.40 | 0.30 | No | Yes |
| 3C 270.1 | S A | Edged | 36 | 148.7 | 0.51 | 0.40 | Yes |
| 4C -02.55 | -- -- | -- -- | -- -- | -- -- | -- | Yes |
| 3C 275.1 | NW C | Edged | 32.2 | 96 | 0.44 | 0.27 | Yes |
| 1253+104 | -- -- | -- -- | -- -- | -- -- | -- | Yes |
| 3C 280.1 | SE B | Recessed | 2.3 | 6.8 | 1.2 | 0.7 | Yes |
| 4C 52.27 | -- -- | -- -- | -- -- | -- -- | -- | Yes |
| 4C -06.35 | NW SE | A D | Edged | Edged | 85.1 | 134.1 | 0.34 | 0.31 | Yes |
| 4C 20.33 | N S | A I | Edged | Edged | 21.4 | 53.2 | 0.4 | 0.35 | Yes |
| 4C 15.45 | SE A | Edged | 2.72 | 4.2 | 0.31 | 0.24 | N |
| 4C 13.55 | NW H | Recessed | 16.5 | 50.1 | 0.44 | 0.33 | Yes |
| 3C 323.1 | SW F | Edged | 7.9 | 28.0 | 0.77 | 0.59 | Yes |
| 3C 336 | S M | Recessed | 16.6 | 56.1 | 0.5 | 0.36 | Yes |
| 3C 342 | E A | Edged | 96.0 | 124.1 | 0.28 | 0.26 | No |
| 3C 351 | NE C | Recessed | 102.6 | 134.9 | 0.38 | 0.35 | Yes |
| 4C 65.21 | NE A | Edged | 7.4 | 11.3 | 0.28 | 0.26 | N |
| 4C 27.38 | -- -- | -- -- | -- -- | -- -- | -- | Yes |
| 4C 56.28 | SE D | Recessed | 4.84 | 9.0 | 0.47 | 0.41 | Yes |
| 3C 407 | -- -- | -- -- | -- -- | -- -- | -- | Yes |
| 3C 432 | SE NW | B F | Edge | Recessed | 32.1 | 60.2 | 0.4 | 0.3 | Yes |
| 2209+152 | NE A | Edged | 8.3 | 16.2 | 0.49 | 0.39 | Yes |
| 4C 14.85 | SE A | Edged | 113.4 | 163.4 | 0.43 | 0.36 | Yes |

Notes: Similar to those of Table 3.
3.3. Hot spots location

The location of the edged or recessed hot spot with respect to the radio core is reported in Tables 5 (a & b) & 6 (a & b) for the RGs and QSRs, respectively. The method used to measure the location of the edged and recessed hot spots is similar to that used in F07. These measurements are represented by the R-parameter defined as the ratio of the distance between the hot spot peak and the radio core of the source to the full extent of the lobe measured from the core along the core-hot spot axis. This parameter is a measure of the amount by which the hot spots are either edged or recessed. It is labeled as $R_E$ and $R_R$ for the edged and recessed hot spots, respectively. These two parameters have been treated separately to check for any difference between the edged HSs in the RGs and the edged HSs in the QSRs, and similarly for the recessed HSs.

The distribution of the R-edged parameter ($R_E$) is shown in Figure 5. The mean $R_E$ for the RGs is 0.93. With a confidence coefficient of 95%, we obtain a margin error of 0.01 with a lower and an upper bound of 0.922 and 0.946, respectively. For the QSRs, the mean $R_E$ is 0.91. With the same confidence coefficient, a margin error of 0.03 is obtained with a lower and an upper bound of 0.882 and 0.938, respectively. The RGs show a slightly larger $R_E$ mean than the QSRs. A KS two-sample test indicates that the maximum difference $D$ between the two cumulative distributions is 0.2670 with a corresponding $P$-value of 0.070. Furthermore, we ran a Student’s T-test to compare the distributions’ means. The test gives a probability, assuming the null hypothesis, of 0.091. It is slightly higher than the critical value of 0.05. The similarity is not very significant in terms of the R-edged parameter ($R_E$).

The distribution of the R-recessed parameter ($R_R$) is shown in Figure 6. The mean $R_R$ for the RGs is 0.777. Using the same confidence coefficient of 95%, we obtain a margin error of 0.07 with a lower and an upper bound of 0.711 and 0.844, respectively. For the QSRs, the mean $R_R$ is 0.805. With the same confidence coefficient, a margin error 0.07 is obtained with a lower and an upper bound of 0.728 and 0.882, respectively. A KS two-sample test shows that the maximum difference $D$ between the two cumulative distributions is 0.1947 with a corresponding P-value of 0.810. Furthermore, we ran Student’s T-test to compare the distributions’ means. The test gives a probability, assuming the null hypothesis, of 0.570. This is much higher than the critical value of 0.05. In terms of the R-recessed parameter ($R_R$), there is no difference between the RGs and the QSRs.

![Figure 4. Distribution of the size of the HSs using the geometrical mean of the largest (HSLAS) and smallest (HSSAS) angular sizes. The bin interval width is 0.1 arcsec.](image-url)
### Table 5a. Values of the R-parameter for the Edged (R_E), Recessed (R_R) Hot Spots and the Asymmetry parameter (Δ) for the 52 Radio Galaxies.

| Source Name (1) | Number of HS (2) | R_E (3) | R_R (4) | Δ (5) |
|----------------|-----------------|---------|---------|-------|
| 3C 6.1         | 2               | 0.95    | 0.93    | 0.98  |
| 3C 13          | 2               | 0.96    | 0.93    | 0.97  |
| 3C 19          | 2               | 0.86    | 0.86    | 1.0   |
| 3C 20          | 2               | 0.79    | 0.92    | 0.86  |
| 3C 34          | 0               | --      | --      | --    |
| 3C 41          | 2               | 0.95 (J)| 0.93    | 0.98  |
| 3C 42          | 1               | 0.9     | --      | --    |
| 3C 55          | 2               | 0.99    | 0.99    | 1.0   |
| 3C 65          | 2               | 0.95    | 0.86    | 0.91  |
| 3C 68.2        | 2               | --      | 0.84    | 0.99  |
| 4C 14.11       | 0               | --      | --      | --    |
| 3C 123         | 2               | --      | 0.81    | 0.60  |
| 3C 132         | 2               | 0.96    | 0.95    | 0.99  |
| 3C 153         | 2               | 0.92    | 0.55    | 0.60  |
| 3C 173.1       | 2               | 0.96    | 0.96    | 1.0   |
| 3C 194         | 2               | 0.95    | 0.89    | 0.94  |
| 3C 197.1       | 2               | 0.83    | 0.88    | 0.94  |
| 3C 200         | 1               | --      | 0.63    | --    |
| 4C 14.27       | 0               | --      | --      | --    |
Notes. Col. (1) lists the source name. Col. (2) reports on the number of hot spots the source has as described in the text. Cols. (3) and (4) the R-parameter for the edged and recessed hot spot, respectively. The letter “J,” here and in the other tables, means the jetted side of the source. Col. (5) gives the asymmetry parameter \( \Delta \), measured as the ratio of the smaller value of R over the larger one.

### Table 5b. Values of the R-parameter for the Edged (\( R_E \)), Recessed (\( R_R \)) Hot Spots and the Asymmetry parameter (\( \Delta \)) for the 52 Radio Galaxies.

| Source Name (1) | Number of HS (2) | \( R_E \) (3) | \( R_R \) (4) | \( \Delta \) (5) |
|----------------|-----------------|---------------|---------------|----------------|
| 3C 217         | 1               | 0.91          | --            | --             |
| 3C 220.1       | 2               | 0.88 (J)      | 0.97          | 0.91           |
| 3C 228         | 2               | 0.98 (J)      | 0.96          | 0.98           |
| 3C 239         | 2               | 0.95          | 0.78          | 0.82           |
| 4C 74.16       | 2               | --            | 0.95          | 0.88           |
| 3C 244.1       | 2               | 0.95          | 0.72          | 0.76           |
| 3C 247         | 2               | 0.93          | 0.95          | 0.98           |
| 3C 252         | 2               | 0.96          | 0.92          | 0.96           |
| 3C 265         | 2               | 0.98          | 0.95          | 0.97           |
| 3C 267         | 2               | 0.97          | 0.97          | 1.0            |
| 3C 268.1       | 2               | 0.97          | 0.94          | 0.97           |
| 3C 277.2       | 2               | 0.94          | 0.85          | 0.91           |
| 3C 280         | 1               | 0.84          | --            | --             |
| 4C 38.35       | --              | --            | --            | --             |
| 3C 289         | 2               | 0.90          | 0.90          | 1              |
| 3C 299         | --              | --            | --            | --             |
| 3C 300         | 1               | 0.93          | --            | --             |
| 3C 323         | 2               | 0.97          | 0.54 (J)      | 0.56           |
| 3C 324         | 2               | 0.92          | --            | 0.91           |
Notes.- Similar to Table 5a.

**Table 6a.** Values of the R-parameter for the Edged (R_E), Recessed (R_R) Hot Spots and the Asymmetry parameter (Δ) for the 46 Quasars.

| Source Name (1) | Number of HS (2) | R_E (3) | R_R (4) | Δ (5) |
|----------------|------------------|---------|---------|-------|
| 3C 9           | 2                | 0.89    | 0.93    | --    | 0.96  |
| 3C 14          | 1                | --      | 0.95 (J)| --    |       |
| 4C -02.04      | 2                | --      | 0.83    | 0.90 (J)| 0.92  |
| 3C 22          | 2                | 0.96    | 0.95    |       | 0.99  |
| 3C 68.1        | 1                | 0.94    | --      | --    |       |
| 3C 79          | 2                | 0.98    | 0.96    | 0.98  |       |
Table 6b. Values of the R-parameter for the Edged ($R_E$), Recessed ($R_R$) Hot Spots and the Asymmetry parameter ($\Delta$) for the 46 Quasars.

| Source Name | Number of HS | $R_E$ | $R_R$ | $\Delta$ |
|-------------|--------------|-------|-------|----------|
| 3C 00.34    | 1            | --    | 0.93  | --       |
| 3C 249.1    | 1            | 0.94  | --    | --       |
| 4C -00.43   | 1            | 0.96  | --    | --       |
| 1136-135    | 1            | 0.94  | --    | --       |
| 3C 263      | 2            | 0.90  | 0.83  | 0.92     |

Notes.- Similar to Table 5a.
| Name      | Type | X | Y | Z    | V    | W    |
|-----------|------|---|---|------|------|------|
| 3C 275.1  | 1    | 0.91 | -- | --   | --   |
| 1253+104  | 0    | --   | -- | --   | --   |
| 3C 280.1  | 1    | --   | 0.85 | --   |
| 4C 52.27  | 0    | --   | -- | --   |
| 4C -06.35 | 2    | 0.92 (J) | 0.88 | --   | 0.96 |
| 4C 20.33  | 2    | 0.87 | 0.94 (J) | --   | 0.93 |
| 4C 15.45  | 1    | 0.62 | -- | --   |
| 4C 13.55  | 1    | --   | 0.95 | --   |
| 3C 323.1  | 1    | 0.98 (J) | --   | --   |
| 3C 336    | 1    | --   | 0.74 | --   |
| 3C 342    | 1    | 0.97 | -- | --   |
| 3C 351    | 1    | --   | 0.87 | --   |
| 4C 65.21  | 1    | 0.88 | -- | --   |
| 4C 27.38  | 0    | --   | -- | --   |
| 4C 56.28  | 1    | --   | 0.47 (J) | --   |
| 3C 407    | 0    | --   | -- | --   |
| 3C 432    | 2    | 0.93 | 0.82 | 0.88 |
| 2209+152  | 1    | 0.92 (J) | --   | --   |
| 4C 14.85  | 1    | 0.9 (J) | --   | --   |

Notes.- Similar to Table 5a.
Figure 5. Distribution of the R-edged parameter ($R_E$) using a bin width interval of 0.05 unit.

Figure 6. Distribution of the R-recessed parameter ($R_R$) using a bin width interval of 0.10 unit.

To further quantify the amount of hot spot asymmetry between the two lobes of a source, we introduce an asymmetry parameter $\Delta$ defined as the ratio of the smaller to the larger value of the $R$-parameter (Tables 5a, 5b, 6a & 6b). Figure 7 shows a histogram of the $\Delta$ parameter distribution. The mean asymmetry parameter $\Delta$ for the RGs is 0.902. With a confidence coefficient of 95%, we obtain a margin error of 0.04 with a lower and an upper bound of 0.854 and 0.951, respectively. For the QSRs, the mean $\Delta$ is 0.889. With the same confidence coefficient, a margin error of 0.05 is obtained with a lower and an upper bound of 0.838 and 0.941, respectively. A KS two-sample test shows that the maximum difference $D$ between the two cumulative distributions is 0.3490 with a corresponding P-value of 0.111. The Student’s T-test to compare the distributions’ means gives a probability of 0.724 assuming the null hypothesis. There is no difference between the RGs and the QSRs in terms of the asymmetry parameter $\Delta$. 
3.4. Hot Spots size and linear-size correlation

Hardcastle et al. [12] 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 [7] and B94 that the hot spot sizes scale with source linear size. Black [13], however, finds no such correlation. Kharb et al. [14] 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 [15]. To check this correlation for our sample of 98 sources, we have plotted the hot spot size (geometrical mean as defined above) against the core – hot spot distance. Figures 8 and 9 show these plots for the RGs and QSRs, respectively. We fitted a simple linear model in the log-log space to the RGs data and obtained a slope of $0.17 \pm 0.06$. For the QSRs, the linear fit gives a slope of $-0.023 \pm 0.059$. 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.
3.5. Physical Properties of Hot spots

For each hot spot, we measured the radio size flux at 8.4 GHz. For a sub-sample of hot spots, the radio spectral index and the X-ray flux density is known (see below). The goal is to use this data to determine further physical properties of the hot spots like the peak frequency and flux density at which the synchrotron source becomes optically thick and the magnetic field. In the coming sections, we show how this can be done for individual sources and the average radio galaxy and QSR hot spot.

3.5.1 The Method. To find self-consistent solutions for the quantities intrinsic source size $\theta$, the turnover frequency $\nu_m$, the turnover flux density $S_m$, and the magnetic field strength $B$, we applied the following method: the measured values $\theta_{\text{obs}}$ are deconvolved with the known beam widths $\theta_{\text{beam}}$ via

$$\theta^2 = \theta_{\text{obs}}^2 - \theta_{\text{beam}}^2$$  \hspace{1cm} (1)
From the beam corrected source size $\theta$, we determined the mean $\theta_{\text{mean}}$ and the corresponding standard deviation $\sigma_\theta$. We calculate $S_m$ at $\nu_m$ (with $S \sim \nu^{-\alpha}$) via the measured flux density $S_{\nu} \text{GHz}$ at the observing frequency $V_{\nu} \text{GHz}$ via

$$S_m = S_{\nu} \left( \frac{V_m}{V_{\nu}} \right)^{-\alpha} \quad (2)$$

We then considered a cube of spectral indices $\alpha_\text{cube}$, turnover frequencies $\nu_\text{cube}$ and magnetic field strengths $B_\text{cube}$. Following equation 2 in Marscher [16], we can then use for each set of these quantities the values for $\alpha_\text{cube}$ and $\nu_\text{cube}$ to recalculate the magnetic field $B_{\text{recalc}}$ and $\theta_{\text{recalc}}$, and the values $\alpha_\text{cube}$ and $B_\text{cube}$ to recalculate $\nu_{m,\text{recalc}}$ $\theta_{\text{recalc}}$ via

$$B = 10^{-5} b(\alpha) \theta^4 \nu_m^5 s_m^{-2} \frac{\delta}{1 + z} \quad (3)$$

Here, $b(\alpha)$ is tabulated by Marscher [16] and is about 3.7 for $\alpha = 0.8$. The redshifts $z$ of the sources are known. The quantity $\delta$ describes the relativistic bulk motion of the hot spot with

$$\delta = \Gamma^{-1}(1 - \beta \cos \phi) \quad (4)$$

Here, $\phi$ is the angle to the line of sight, $\beta = \nu/c$ is the hot spot bulk motion $\nu$ in units of the speed of light $c$ and $\Gamma = \left(1 - \beta^2\right)^{-1/2}$ the dilatation factor. We have analyzed two cases: No boosting with $\delta = 1.0$ and a light boosting with $\delta \approx 1.6$. The case with $\delta = 1.0$ implies sub-relativistic speeds or very large angles to the line of sight. The boosting case corresponds to high speeds and smaller angles to the line of sight. As an example, we use $\delta \approx 1.6$ which corresponds for instance to a speed of about $\beta = 0.5$ and the angle to the line of sight $\phi \approx 20^\circ$ or $\beta = 0.8$ and the angle to the line of sight $\phi \approx 40^\circ$. These values correspond to kinematical signatures typically found for jets on the kiloparsec scale (e.g., [17], [18]).

Using $\sigma_\theta$ from above, $\sigma_{\log(\theta)} = 1.0$, $\sigma_{\nu_m} = 0.25 \text{ GHz}$, we calculate $\chi^2$ values to judge on the quality of the self-consistency:

$$\chi_\theta^2 = \frac{\theta_{\text{mean}}^2 - \theta_{\text{recalc}}^2}{\sigma_\theta^2} \quad (5)$$

$$\chi_B^2 = \frac{\log^2(B_\text{cube}) - \log^2(B_{\text{recalc}})}{\sigma_{\log(\theta)}^2} \quad (6)$$

$$\chi_{\nu_m}^2 = \frac{\nu_{\text{cube}}^2 - \nu_{\text{recalc}}^2}{\sigma_{\nu_m}^2} \quad (7)$$

These are then combined to a general $\chi^2$ value of

$$\chi^2 = \chi_\theta^2 + \chi_B^2 + \chi_{\nu_m}^2 \quad (8)$$

The resulting self-consistent solutions allow for a range of possible magnetic fields and turnover frequencies. A further constraint can be introduced by using the fact that a number of hot spots with known radio fluxes and radio spectral indices $\alpha_{\nu}$ have now been detected in the X-ray domain ([19], [20]).
[20], and [21]). Assuming an SSC model following equation 4 by Marscher [16] we can calculate the expected X-ray flux densities at an energy \( E_{\text{keV}} \) of 1 keV via

\[
S^\nu_{\nu}(E_{\text{keV}}) \approx d(\alpha) \ln \left( \frac{V^2}{V_m} \right) \theta^{-2(2\alpha+3)} \nu_m^{-(3\alpha+5)} S_m^{2(\alpha+2)} E_{\text{keV}}^{-\alpha/2} \left[ (1+z)/\delta \right]^{2(\alpha+2)}
\]

(9)

Here, \( d(\alpha) \) is tabulated by Marscher [16] and is close to 15 for \( \alpha = 0.8 \). Using \( \sigma_{\text{obs,1 keV}} \approx 0.1 \, nJy \) as a typical uncertainty of the X-ray flux measurements, \( S_{\text{obs,1 keV,mean}} \) as the average observed X-ray flux density and the uncertainty \( \sigma_{\nu} \approx 0.25 \) from the distribution of X-ray detected hot spots (see references above), we calculate

\[
\chi^2_{\nu} = \frac{\alpha_{\text{obs,mean}} - \alpha_{\text{cube}}}{\sigma_{\nu}^2}
\]

and

\[
\chi^2_{\text{SSC}} = \frac{S_{\text{obs,1 keV}} - S_{\text{SSC,1 keV}}}{\sigma_{\text{obs,1 keV}}^2}
\]

(10)

(11)

These quantities are then combined to a general \( \chi^2 \) value of

\[
\chi^2 = \chi^2_{\nu} + \chi^2_{\nu} + \chi^2_{\text{SSC}} + \chi^2_{\text{SSC}} = \chi^2 + \chi^2 + \chi^2_{\text{SSC}}
\]

(12)

Marscher [16] points out that it is not appropriate to use a Gaussian FWHP source sizes \( \theta_G \) (as typically retrieved from radio maps) in the above formula (9) as these sizes are substantially smaller than the diameter of a spherical source (for which the above formulae have been derived). He suggests to use \( \theta = 1.8 \, \theta_G \). However, a visual inspection of the more spatially resolved hot spots source structures shows that neither a Gaussian nor a spherical source model fully describes the observed hot spot structures; see e.g., the hot spot structure of 3C173.1 ([15]) or structures of simulated hot spots as presented by Massaglia et al. [22]. However, given that they typically consist of a central shock front embedded in some envelope of slightly larger size, a Gaussian can describe this situation in a more appropriate form than a sphere. Hence, we have resorted to a value of \( \theta = 1.0 \, \theta_G \). This constrains the domains of high self-consistency to well defined regions in the \( \alpha_{\text{cube}}, \nu_{\text{cube}} \) and \( B_{\text{cube}} \) cube. Finally, we attributed to each pixel in this cube the value exp\( (-\chi^2) \). This value characterizes the quality of self-consistency and reaches a maximum at the location of maximum agreement between the measured or initially adopted and the recalculated values.

We performed these calculations in two ways: (1) we did it for all individual sources using the mean SSC fluxes as constraints; and (2) we did it for the average radio galaxy and QSR. Here, we assume that the scattering efficiencies are similar for the individual sources in the subgroups. For each subset, we then scale the mean SSC flux densities using the ratio between the mean radio flux densities of all sources and the mean radio flux densities of all sources for which the SSC flux density had been measured.

3.5.2 Results. We have analyzed the sample of RGs and QSRs separately. On average the QSRs are located at a slightly higher redshift. For the sample of RGs we found 3 sources and for the QSRs 4 objects for which the X-ray flux density of the hot spots have been published ([19], [20], and [21]). The corresponding X-ray flux densities are listed in Table 7. For these sources, our calculated SSC X-ray fluxes match the measured X-ray fluxes to within an uncertainty of 10% to 30%. In Table 7, we list the source name and literature reference, followed by the redshift \( z \), the geometrical mean of the observed hot spot size \( \theta_{\text{obs}} \), the 8.4 GHz flux density \( S_{\text{8.4 GHz}} \), the radio spectral index \( \alpha \), and the observed 1–keV X-ray flux density \( S_{\text{1 keV}} \). We then list for a boosting factor \( \delta = 1.0 \) and \( \delta = 1.6 \) the 1–keV SSC flux density recovered by the model, and the peak frequency \( \nu_{\text{max}} \) of the optically thick synchrotron
spectrum. For the average RG and QSR, we list the mean values for $z$, $\theta_{\text{obs}}$, $S_{8.4\, \text{GHz}}$, and density $S_{8.4\, \text{GHz}}$, the radio spectral index $\alpha$, and the observed 1 keV X-ray flux density $S_{1\, \text{keV}}$.

**Table 7.** X-ray flux densities for different two different models as compared to the observed.

| Source  | Ref. | $z$ | $\theta_{\text{obs}}$ [mas] | $S_{8.4\, \text{GHz}}$ [Jy] | $\alpha$ | $S_{1\, \text{keV}}$ [nJy] | $SSC_{\text{model}}$ [nJy] | $B$ [Gauss] | $\nu_{\text{max}}$ [GHz] | $SSC_{\text{model}}$ [nJy] | $B$ [Gauss] | $\nu_{\text{max}}$ [GHz] |
|---------|------|-----|------------------|-----------------|-------|-----------------|----------------|-------|-----------------|----------------|-------|-----------------|
| 3C 228  | 19   | 0.552 | 0.446 | 0.243 | 0.80 | 1.30 | 1.30 | -3.68 | 0.047 | 1.27 | -4.25 | 0.022 |
| 3C 280  | 19   | 0.996 | 0.269 | 0.500 | 0.79 | 0.79 | 0.83 | -2.75 | 0.094 | 0.82 | -3.10 | 0.094 |
| 3C 330  | 20   | 0.550 | 0.494 | 0.140 | 0.80 | 0.09 | 0.12 | -3.50 | 0.034 | 0.09 | -3.88 | 0.028 |
| 3C 207  | 21   | 0.684 | 0.469 | 0.052 | 0.88 | 0.27 | 0.14 | -3.88 | 0.028 | 0.26 | -4.44 | 0.019 |
| 3C 263SE| 20   | 0.646 | 0.390 | 0.0153 | 0.84 | 1.7  | 1.89 | -3.50 | 0.072 | 1.52 | -3.88 | 0.059 |
| 3C 263NW| 20   | 0.646 | 0.460 | 0.0153 | 0.84 | 0.06 | 0.10 | -4.25 | 0.019 | 0.07 | -4.63 | 0.016 |
| 3C 275.1 | 19  | 0.550 | 0.345 | 0.086 | 0.84 | 1.70 | 1.73 | -4.06 | 0.034 | 1.44 | -4.63 | 0.028 |
| 3C 351  | 20   | 0.370 | 0.395 | 0.135 | 0.65 | 4.00 | 4.21 | -4.06 | 0.047 | 3.96 | -4.62 | 0.025 |
| Galaxies| 0.758 | 0.469 | 0.104 | 0.80 | 0.258 | 0.18 | -3.50 | 0.034 | 0.20 | -3.87 | 0.031 |
| QSR     | 0.995 | 0.408 | 0.067 | 0.80 | 1.180 | 0.99 | -3.87 | 0.031 | 1.36 | -4.44 | 0.028 |

Notes to Table 7 - Following the source name and literature reference (see below) we list the redshift $z$, the geometrical mean of the observed hot spot size $\theta_{\text{obs}}$, the 8.4-GHz flux density $S_{8.4\, \text{GHz}}$, the radio spectral index $\alpha$, and the observed 1 keV X-ray flux density $S_{1\, \text{keV}}$. We then list for a boosting factor $\delta = 1.0$ and $\delta = 1.6$ the 1 keV SSC flux density recovered by the model, and the peak frequency $\nu_{\text{max}}$ of the optically thick synchrotron spectrum. For the average RG and QSR, we list the mean values for $z$, $\theta_{\text{obs}}$, $S_{8.4\, \text{GHz}}$, and $S_{1\, \text{keV}}$. Radio spectral indices and observed X-ray fluxes are taken from [19], [20], and [21].

In Figure 10 we show results from a cut through the data cubes that pass through the point of highest $e^{-x^2}$ value. We find typical magnetic field strengths of $10^{-3}$ to $10^{-4}$ Gauss, for spectral indices around $\alpha = 0.8$, and turnover frequencies of the order of $\nu_{\text{max}} = 0.03$ GHz. This indicates that the differences between the low and high redshift sample are small. Consistent with equations (9) and (2) we find for the higher boosting factor typically a 3 times lower magnetic field and a 1.5 times lower turnover frequency.

![Figure 10](image.png)

**Figure 10.** Plot of the frequency $\nu_{\text{max}}$ as a function of the magnetic field $B$. 


The result in Table 7 is rather robust and not very sensitive to reasonable assumptions on the hot spot source structure. Assuming that more extended flux does not contribute significantly to the SSC X-ray emission and placing half the flux density within an embedded component of half the intrinsic source size results for $\delta = 1$ and a spectral index of $\alpha = 0.3$ in $B = 10^{-3.5}$ Gauss and $\nu_m=0.019$ GHz for the average RG and in $B = 10^{-4.0}$ Gauss and $\nu_m=0.017$ GHz for the average QSR. Similarly, we obtain for $\alpha = 0.8$ in $B = 10^{-3.7}$ Gauss and $\nu_m=0.041$ GHz for the average RG and $B = 10^{-3.9}$ Gauss and $\nu_m=0.044$ GHz for the average QSR. We conclude that for the data listed in Table 7 the uncertainties for the magnetic field strengths are about 0.5 in the exponent and about 0.01 GHz for the turnover frequencies.

With an average of $\nu_m=0.03$ GHz, the turnover frequencies are rather low. However, for kpc-scale extragalactic jets, the intrinsic deconvolved source sizes of about 0.3" around $z = 0.8$, i.e., typically a linear diameter of 4 kpc, are in the range of measured and predicted hot spot source sizes including the environment they are embedded in (e.g., [5], [22]).

4. Summary
We have presented the hot spot analysis of a sample of 98 FR II radio sources (52 RGs and 46 QSRs). Our primary results can be summarized as follows:

1. The RGs tend to have more edged (and recessed) HSs than the QSRs.
2. The QSRs appear to have more compact HSs than RGs.
3. The similarity is not very significant in terms of the R-edged parameter ($R_E$).
4. There is no difference between the RGs and the QSRs in terms of the R-recessed parameter ($R_k$).
5. There is a significant correlation between the hot spot size and the linear size of the source for the 52 RGs, but not for the 46 QSRs. This lack of correlation for the QSRs must be explored further in light of the radio source models.
6. For spectral indices around $\alpha = 0.8$ and turnover frequencies of the order of $\nu_m=0.03$ GHz, we find typical magnetic field strengths of $10^{-3}$ to $10^{-4}$ Gauss. This indicates that the differences between the low and high redshift sample are small. Consistent with equations (9) and (2) we find for the higher boosting factor typically a 3 times lower magnetic field and a 1.5 times lower turnover frequency.

As our study shows, the high-quality, detailed images of the hot spots are essential to make a comparative study of RGs and QSRs to better understand their properties and their implications for models of radio sources.

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