Samples and statistics of CSS and GPS sources

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The dates of receipt and acceptance should be inserted later

Several samples have been proposed in the last years in order to study the properties of intrinsically small sources. In this paper, we review the properties of the main samples that are currently available, both selected on the basis of spectral index and of morphology. As a result of the work in this area, large numbers of intrinsically small sources have been found. We summarize the present status of hot spot advance measurements, listing 18 sources with available VLBI data. The mean hot spot separation velocity is \( v_{\text{sep}} = (0.19 \pm 0.11) h^{-1} \) c and the kinematic ages span the range from 20 to 3000 years. Finally, we present a brief outlook on the use of future instrumentation in order to improve our understanding of radio source evolution. Prospects for VSOP2, e-VLA, e-MERLIN, LOFAR, ALMA, and Fermi are suggested.

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1 Introduction

Studies of individual objects are certainly valuable to gain information about the physics of radio sources. However, a general understanding of the triggering and evolution of radio activity can only be obtained with a population-based approach. Of course, since one can not study all galaxies, we are forced to select samples that we believe are best suited to answer the basic questions we are facing. Since all selection criteria are somehow biasing our results, it may be important to summarize the characteristics of the various works. This is particularly relevant in our field, where selection on spectra and morphology can be really confusing!

The first studies on Compact Steep Spectrum (CSS) and Gigahertz Peaked Spectrum (GPS) sources were performed on the 3CR and the Peacock & Wall catalogues (Spencer et al. 1989, Fanti et al. 1990). The number of sources selected in the early days did not exceed a few dozens, and these sources were typically quite powerful. By the time of the Kerastari meeting (2002), the interest in larger and deeper samples was already clear, as documented by the appearance of works based on the B3/VLA sample (\( S_{\text{1.4}} > 0.8 \) Jy, Fanti et al. 2001), the S4 sample (\( S_{\text{5}} > 0.5 \) Jy, Saikia et al. 2001), and the FIRST survey (\( S_{\text{5}} > 0.15 \) Jy, Marecki et al. 2003). In the concluding remarks, the need for additional samples of radio sources was clearly stated, in order to inform us about their volume densities and evolution (Woltjer 2003).

However, building a sample of young sources is a task that takes a lot of effort. First, since our interest lies in the short initial part of the life of radio sources, we are by definition looking for rare targets. Therefore, large areas have to be investigated, requiring large fields of view but without giving up on resolution.

Secondly, the well known relation between peak frequency (\( \nu_{\text{peak}} \)) and linear size (\( LS \)) and the large possible range of \( \nu_{\text{peak}} \) (between about 100 MHz and some 10’s GHz) make it extremely inefficient to select candidates of all sizes/ages. As a consequence, samples tend to focus on sub-classes and it is difficult to obtain an unbiased and homogeneous view of the evolution.

Finally, the follow up work can also take a considerable amount of time. Optical data are needed to determine the host type (galaxy vs. QSO) and possibly the redshift (to tie the angular dimension to a linear scale). VLBI images are also important to exclude core-jet sources and eventually determine the kinematic ages, a process that by itself requires a few to several years.

In the remainder of this paper, we will review some of the main results obtained on the study of samples of CSS and GPS sources in the period between the Kerastari meeting (2002) and today. Section 2 will be devoted to a survey of the various samples, divided among those selected on the spectral properties and on the morphology, with a short discussion of the two approaches. In Sect. 3 we will report some statistics and in particular we will summarize the present status on hot spot advance measurements. Finally, some suggestions for the future are given in Sect. 4.

2 Samples

2.1 Spectrally selected samples

2.1.1 The B3/VLA CSS Sample

Starting from the 1049 sources in the B3/VLA sample (Vigotti et al. 1989, Fanti et al. 2001) have searched for Compact Steep Spectrum sources, imposing selection criteria on both compactness (\( LS < 20 h^{-1} \) kpc) and spectral index (\( \alpha_{1.5}^{1.0} > 0.5 \)). A further selection was applied on the low frequency

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flux density \((S_{0.4\,\text{GHz}} > 0.8\,\text{Jy})\), providing a final sample of 87 sources.

This number makes it the largest sample of CSS sources with high quality information; statistically, the 87 sources represent the 23% of the population in the corresponding flux density bin, a percentage similar to that found in earlier works by Fanti et al. (1995). Thanks to optical spectra or photometry, 62% of the sources have a measured redshift; the final range is \(0.02 < z < 4.1\), with a median \(z = 1.05\). This quite large distance range combined with the flux density measurements corresponds to radio powers in the range \(10^{25} < P_{0.4\,\text{GHz}} < 10^{29}\,\text{[W Hz}^{-1}]\). Therefore, besides a number of very luminous sources, some members of the sample are also relatively low power radio sources.

The first paper, beside defining the sample, presented also the results of multi-frequency VLA observations and a discussion of properties such as the morphology, the presence of spectral steepening at high frequency, and the detection of significant polarization (4% at 5 GHz, and 6% at 8 GHz). Moreover, a study of the number counts with respect to the largest linear size \((\text{LLS})\), revealed a power law relation \(dN/d(\text{LLS}) \propto \text{LLS}^{-0.6}\).

Follow up studies on the sample have greatly clarified the nature of both the sources and the medium in which they advance. Multi frequency observations with various interferometers (EVN, VLBA, MERLIN) have probed different angular scales, revealing both Compact Symmetric Objects (CSO) and Medium Symmetric Objects (MSO), besides a number of naked cores. Dallacasa et al. (2002a,b), Orienti et al. (2004). High-frequency, high-resolution data have also been obtained with the VLA at 15 GHz. This has also permitted a spectral index study over a large range of frequency; the continuous injection model is in good agreement with the data for \(\geq 85\%\) of the sources (Rossetti et al. 2006). Finally, polarization observations have also been obtained, and they have been exploited to discuss the ambient Faraday medium properties (Fanti et al. 2004; Rossetti et al. 2008, 2009).

In total, the sample has produced a series of 7 papers (so far) and a large number of citations (90 at the time of writing). Thanks to its large size and the huge amount of work with a broad range of techniques, it is probably the best source of knowledge about not only the evolution of radio sources but also the properties of the inner regions of galaxies. It would be great if the B3/VLA sample were expanded to a lower flux density threshold, although it will be difficult to keep up with the great quality that has been done so far.

2.1.2 FIRST-based survey(s) of CSS sources

Another sample that has given rise to a large number of works of high quality and impact is the one developed by the Toruń group in the same years. It was discussed at the Kerastari meeting Marecki et al. (2003), although a more detailed discussion is surely the one given in Kunert et al. (2002). The starting ground for this sample is the FIRST survey, which was supposed to provide information about structure. Indeed, compactness \((\text{LAS} < 3")\) and steep spectrum \((\alpha_{1.4} > 0.5)\) are again the basic selection criteria. This sample is also flux density limited, with a threshold of \(S_5 > 150\,\text{mJy}\) (corresponding to the B3/VLA CSS sample selection for a spectral index \(\alpha_{0.4} = 0.67\)).

These selection criteria point to a population that is quite similar to the one sampled by the B3/VLA CSS works: the median redshift is \(z = 1.085\), the radio luminosity range is \(10^{26} < P_{1.4} < 10^{28}\,\text{[W Hz}^{-1}]\). Indeed, the two studies partly overlap, with a handful of objects found in both samples.

The sample has been studied in detail in a series of 5 papers, devoted to the study of the morphology of the objects on different angular scales, using MERLIN and VLA on large scale Kunert et al. (2002), Kunert-Bajraszewska et al. (2005), MERLIN and EVN/VLBA for smaller sources Marecki, Kunert-Bajraszewska (2006), and the VLBA for the most compact objects Kunert-Bajraszewska, Marecki (2006, Kunert-Bajraszewska & Marecki 2007). In total, images have been presented for 46 sources, including 11 MSOs.

One of the goals of this project was to understand whether low power CSS sources were the progenitors of classic FR1 sources. No FR1 morphology was revealed for sources within the host galaxy, implying that pressure plays a significant role. On the other hand, it has been proposed on the basis of the morphology and nuclear powers that some sources in the sample could be candidate restarted or fading sources. This includes a broad absorption line (BAL) quasar, with asymmetric two-sided jet morphology.

To better clarify the evolutionary paths of all compact sources, a second sample selected from the FIRST survey has also been presented in this workshop Kunert-Bajraszewska et al. (2009). This new sample does not overlap with the previous one and it is focused on less bright sources \((70\,\text{mJy} < S_{1.4} < 1.0\,\text{Jy})\) with steeper spectral index \((\alpha_{1.4} > 0.7)\), thus increasing the incidence of low power and candidate fader compact sources.

2.1.3 The GPS 1 Jy sample

The two above samples have selection criteria that exclude sources with a spectral peak above a few GHz. Indeed, a selection of CSS is relatively straightforward to obtain, since the spectrum is optically thin in the GHz domain. If we are interested in smaller and presumably younger radio sources, we need to consider samples of GPS sources, whose selection is certainly a more complex process. Mostly because of this, one of the main GPS sample available is still the GPS 1 Jy sample presented by Stanghellini et al. (1998) and already discussed at the Kerastari meeting Stanghellini (2003).

The GPS 1 Jy sample consists of 33 objects, selected with a spectral peak in the range \(0.4 < \nu_{\text{peak}} < 6\,\text{[GHz]}\), a steep spectral index in the optically thin part \((\alpha > 0.5)\) and a 5 GHz flux density \(S_5 > 1\,\text{Jy}\). As we consider objects with higher spectral peak, the host start to become contaminated by quasar, although \(> 50\%\) of them are still galaxies.
Among the most recent results derived from this sample, we can refer to the follow up works on the nature of its members, carried out by Stanghellini et al. (2005), who looked at the presence of extended radio emission or with VLBI observations. A search for molecular gas has also been performed, but none was found (O'Dea et al. 2005).

2.1.4 The Parkes 0.5 Jy GPS sample

A southern counterpart to the GPS 1 Jy sample is the Parkes 0.5 Jy sample (Snellen et al. 2002). Selected from multi-wavelength Parkes data, it is somewhat deeper \( S_{2.7} > 0.5 \) Jy and contains 49 sources.

An interesting feature of this sample is that it contains only sources identified with galaxies; the host galaxies have all been identified (de Vries et al. 2007), and redshifts are measured for 80% of sources, yielding a range of 0.17 < z < 1.53. Recent EVN observations of 15 sources show mini-double-lobe radio structure (Liu et al. 2007), confirming that CSO morphologies outnumber core-jets when only galaxies-hosted GPS are considered.

2.1.5 Extreme GPS samples: High Frequency Peakers

The problem of the contamination by core-jet variable sources becomes really dramatic when extreme GPS sources are considered. A sample of so-called High-Frequency Peaker (HFP, \( \nu_{\text{peak}} > 5 \) GHz) sources has been selected by Dallacasa et al. (2000) in order to find objects with the smallest \( L_S \) and therefore possibly the smallest age (< 500 yrs): a cross correlation of the Green Bank (GB) survey and the NVSS, followed up by multi-frequency VLA observations, has yielded a sample of 55 genuine (i.e. not variable) HFPs.

A large fraction of objects are hosted by quasars (36/55). Two frequency VLBA observations have revealed a dichotomy between galaxy hosted HFPs, which have double or triple morphology, and QSO hosted HFPs, which tend to be unresolved or core-jets (Orienti et al. 2006). Other clues on the nature of HFPs in the sample have been obtained by studying HI absorption, spectral variability, and polarization, and are discussed in the exhaustive review given at this conference by Orienti et al. (2009).

2.2 Samples selected on morphology

2.2.1 The CORALZ sample

The B3/VLA and the FIRST based samples were specifically designed to focus on CSS sources selecting on spectral index. Since this can somehow bias the results (e.g. excluding the most compact sources), Snellen et al. (2004) have selected a sample of Compact Radio sources at Low Redshift (CORALZ) without any spectral index constraint. The sample is obtained from cross-correlation of the FIRST with the APM/POSS and WENSS regions, selecting sources with a \( S_{\text{peak}} > 100 \) mJy, a \( L_S < 2' \), and a redshift z < 0.2.

The sample consists of 28 objects, and it is 95% complete in the range 0.005 < z < 0.16 (17 objects). Interestingly, an a posteriori look at the spectra of these sources confirms that they are essentially all CSS (10) or GPS (6). From a morphological point of view, EVN, MERLIN, and Global VLBI images reveal that about a half of the sources in the sample are CSOs (de Vries et al. 2009). Since the sources are all relatively nearby, an accurate determination of proper motion in the components should actually be feasible within relatively short time scales.

Another remarkable consequence of the low distance of the objects in the sample is that they have quite low radio luminosity, namely in the range 22.96 < Log\( P_S < 25.25 \) [W Hz\(^{-1}\)]. Finally, it should also be easier to follow up the sources in other wavebands, such as the X-rays or the CO lines (see e.g. Mack et al. 2009).

2.2.2 The COINS and VIPS samples

If one neglects the spectral classification, an interesting way to select candidate young sources is to look at their parsec scale structure. This is ideally done by looking at the images available thanks to large VLBI surveys. A successful example of such an approach is the sample of COIns Observed In the Northern Sky (COINS, Peck & Taylor 2000). It contains 52 candidates, selected from large VLBI surveys with \( S_S > 100 \) mJy and nearly equal double structure or core with emission on either sides.

The selection criteria themselves makes VLBI follow ups relatively more straightforward. Multi-frequency, multi-epoch VLBI observations have confirmed the CSO nature of at least 17 candidates and allowed the measurement of hot spot advance velocities (or limits). The works on the COINS sample by Gugliucci et al. (2005, 2007) have indeed provided the largest amount of new age estimates (3 sources, ranging between 20 ± 4 to 3000 ± 1490, in years) and limits (9 sources, in the range 280–2220 yr) since the Kerastari meeting (see also Sect. 3.1).

A similar approach has been applied more recently to the large dataset provided by the VLBA Imaging and Polarimetry Survey (VIPS), which contains 1127 sources imaged at 5 GHz (Helmoldt et al. 2007). A total of 103 CSO candidates have been selected from this survey and are currently under review for confirmation (Tremblay et al. 2009).

2.3 Samples: summary

As discussed in the previous sections, the selection of samples of intrinsically small sources can be done on the basis of the spectral properties or on the morphology. Both approaches have advantages and disadvantages. On one hand, it is relatively straightforward to obtain a starting list simply by cross-correlating catalogues at different frequencies. Of course, things become more and more complex when one wants to consider sources with higher \( \nu_{\text{peak}} \): high frequency catalogues are less numerous and extended; contamination by core-jet sources and flaring blazars can become
significant. At some point, the information on morphology becomes necessary.

On the other hand, starting from the information on morphology can provide from the very beginning a lot of useful information. The distinction between truly compact sources and beamed core-jets is somewhat simpler, and the discussion of advance motions can often be started with just one additional set of observations. However, the availability of the initial data is not as large as in the case of spectral selection and, moreover, these master lists can be severely biased. For example, there are large intervals of spatial frequencies that are not well sampled by surveys with present instruments. This makes a discussion of the statistical significance of the obtained results certainly more difficult. See also on this topic the relevant work done on MSO by Augusto et al. (2006, 2009).

In any case, both spectrum and morphology are essential pieces of information. Whatever the starting approach, there is always an interaction between the two methods, whose complementarity is clear. Finally, it is also worth mentioning an entirely different methodology, such as the one based on the low polarization criterion (see e.g. Cassaro, Dallacasa & Stanghellini 2006, 2009).

### 3 Statistics

As we showed in the previous section, there has been clearly a remarkable amount of work on the topics of selecting and studying samples of compact sources. Numbers are therefore getting much larger than what was available in 2002. As for CSS sources, the master lists of the B3/VLA and the two FIRST based samples sum up to a total of 191 sources (although in the end some of them were rejected/duplicated). The radio luminosity range is also being pushed to lower values, in the effort to include also low power CSS with FR1 morphologies. The B3/VLA and the brightest FIRST sample extend over the luminosity range $10^{25} < P_{0.4} < 10^{29}$ [W Hz$^{-1}$], while the new FIRST based sample is eventually trying to get below the $10^{25}$ W Hz$^{-1}$ threshold.

Indeed, Giroletti, Giovannini & Taylor (2005) have presented at least a couple of compact sources that are FR1-like both in morphology and radio luminosity: $0258+35$ ($z = 0.016$, $P = 10^{24.4}$ W Hz$^{-1}$, $LS = 1.5$ kpc), and $1855+37$ ($z = 0.055$, $P = 10^{24.3}$ W Hz$^{-1}$, $LS = 7$ kpc). However, these sources are missed in present samples, either because of a spectral index slightly flatter than $\alpha = 0.5$ ($0258+35$) or a low flux density ($S_{0.4} < 0.8$ Jy, $1855+35$).

Another boundary to cross is on the size, with an interest on the more elusive MSO. Augusto et al. (2009) reports an interesting search for such objects, considering 157 candidates.

Numbers are also getting large if we consider sources with higher $v_{\text{peak}}$. Labiano et al. (2007) have compiled a master list of 172 GPS and HFPs. Here, the main problem is still discussing the optical counterpart: 59 sources are hosted by QSOs, 82 by galaxies, and 31 are still empty fields. Redshifts are available for 108 sources (63%), covering the range $0.008 < z < 3.77$, with a median value of $z = 0.76$. The flux densities are in the range $47 \text{ mJy} < S < 6.5 \text{ Jy}$ (median 0.77 Jy, mean 1 Jy), although the different spectral properties make this values not entirely homogeneous.

As anticipated by Woltjer (2003), we are starting to capitalize on such large numbers in order to get information about volume densities and evolution. For example, Tinti & de Zotti (2006) considered a sample of 111 GPS and found that the observed redshift and peak frequency distributions are in agreement with simple luminosity evolution of individual sources. A decrease of the emitted power and of the peak luminosity with source age or with decreasing peak frequency was also required. Completion of the information on the host properties, including redshift measurement, and a less ambiguous selection of the GPS samples could help to converge on this model.

### 3.1 Ages

Surely, we are getting also some progress on the evolution of MSO. Polatidis & Conway (2003) had summarized available kinematic age studies, reporting 10 estimates and 3 lower limits. Observations in recent years have contributed to increase the number of measurements and in some cases to refine previous figures. In Table 1 we report the current available estimates from the literature or from new data. Data are typically measured from hot spot to hot spot.

The number of measurements has almost doubled. In total, there are now 18 estimates, ranging from 20 to 3000 years (mean age 967 yrs, median 435 yrs). Sources span a range in linear size between 2 and $\sim 120$ parsecs. The hot spot velocities are still consistent with the values reported by Polatidis & Conway (2003). The current average velocity is $v_{\text{sep}} = (0.19 \pm 0.11) h^{-1}c$. A number of lower limits have also been found (e.g. by Gugliucci et al. 2005), and non-radial motions seem also to be present in a few sources (Stanghellini 2009).

Whether all sources actually show hot spot motion is still to be solved. Limits on motions have been found in several cases (e.g. by Gugliucci et al. 2005). Moreover, non-radial motions seem also to be present in a few sources (Stanghellini 2009) and it has been reported at least one case of inward moving hot spots (Tremblay et al. 2008). It is encouraging to report several new works presenting VLBI images of large numbers of GPS and CSOs, e.g. Liu et al. (2007, 19 GPS sources), Tremblay et al. (2009, 103 CSO candidates), de Vries et al. (2003, for the CORALZ sample). One can then expect an increase of advance motion measurements in the next few years.

### 4 Looking forward to the next meeting...

Our community has certainly made a great advance in the understanding of the physics and evolution of radio sources
Table 1  Hot spot advance velocity and kinematic age estimates. Unless otherwise noted, measurements are from hot spot to hot spot.

| Source          | z     | Size (pc) | Velocity (c) | Age (yr) | Reference         |
|-----------------|-------|-----------|--------------|----------|-------------------|
| 0035+227        | 0.096 | 21.8      | 0.15         | 450      | 1                 |
| 4C31.04 (0116+319) | 0.059 | 70.1      | 0.45         | 501      | 2                 |
| 0108+388        | 0.669 | 22.7      | 0.18         | 404      | 1                 |
| J0204+0903      | n/a   | 18.3*     | 0.07*        | 240      | 3                 |
| J0427+4133      | n/a   | 1.3*      | 0.06*        | 20       | 3                 |
| 0710+567        | 0.460 | 109.0     |              | 1836     | 4                 |
| 1031+567        | 0.460 | 109.0     |              | 1836     | 4                 |
| 1245+676        | 0.107 | 9.6       | 0.16         | 188      | 4                 |
| OQ208 (1404+286) | 0.077 | 7.0       |              | 10       | 219               |
| CTD 93 (1607+268) | 0.473 | 240       |              | 2200     | 6                 |
| 1718-649        | 0.014 | 2.0       | 0.07         | 91       | 1                 |
| J1826+1831      | n/a   | 41.9*     | 0.015*       | 2600     | 7                 |
| 1843+356        | 0.763 | 22.3      | 0.39         | 180      | 4                 |
| 1934-638        | 0.183 | 85.1      | 0.17         | 1603     | 1                 |
| 1946+708        | 0.101 | 39.4      |              | 1261     | 1                 |
| 2021+614        | 0.227 | 16.1      | 0.14         | 368      | 4                 |
| 2352+495        | 0.238 | 117.3     | 0.12         | 3003     | 4                 |

(*) Size in mas, velocity in mas yr$^{-1}$. Motion is measured from hot spot to core.

References: 1. This work; 2. Giroletti et al. (2003); 3. Gugliucci et al. (2005); 4. Polatidis & Conway (2003) and references therein; 5. Luo et al. (2007); 6. Nagai et al. (2006); 7. Gugliucci et al. (2007).

thanks to the samples discussed here. Upcoming new instrumentation can be used to take further important steps. The need to consider low power sources seems to be already quite clear; the increased sensitivity of e-VLA and e-MERLIN and the use of phase referenced VLBI observations will certainly help this cause. e-VLA and e-MERLIN will also be important to obtain images on the intermediate scales somehow neglected so far. LOFAR will also offer a great opportunity to assess the fraction of young sources that show evidence of remnants of previous stages of activity, while ALMA could discover the youngest radio sources with the highest $\nu_{\text{peak}}$.

The physics of the radio sources will also be probed thanks to high-energy astronomy, and in particular by the recently launched Fermi Gamma-ray Space Telescope (formerly GLAST) which with its sensitivity and monitoring capability will provide statistically significant results. In any case, the search for outliers and the monitoring will remain an important task. It is also likely that constraints on spectral index will have to be released in order to obtain a coherent view of various populations.

Space VLBI is also entering a new era. In particular, VSOP2 will be launched in 2012 and it could be a fantastic machine for hot spot advance measurements. The angular resolution will be as high as 38 $\mu$as at 43 GHz and will significantly shorten the time scales for the detection of motions in the most compact sources. A pre-launch survey could be necessary to find the best candidates - and in particular to assess the numbers of sources that can be most successfully studied at 8, 22, and 43 GHz.

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