A survey of Low Luminosity Compact sources

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Based on the FIRST and SDSS catalogues a flux density limited sample of weak Compact Steep Spectrum (CSS) sources with radio luminosity below $10^{26}$ W Hz$^{-1}$ at 1.4 GHz has been constructed. Our previous multifrequency observations of CSS sources have shown that low luminosity small-scale objects can be strong candidates for compact faders. This finding supports the idea that some small-size radio sources are short-lived phenomena because of a lack of significant fuelling. They never ‘grow up’ to become FR I or FR II objects. This new sample marks the start of a systematic study of the radio properties and morphologies of the population of low luminosity compact (LLC) objects. An investigation of this new sample should also lead to a better understanding of compact faders. In this paper, the results of the first stage of the new project - the L-band MERLIN observations of 44 low luminosity CSS sources are presented.

1 Introduction

The Gigahertz-Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) sources form a well defined classes of radio objects whereas GPS sources are considered to be entirely contained within the extent of the narrow-line region (≤ 1 kpc). CSS sources are thought to extend to the size of the host galaxy (≤ 20 kpc). GPS/CSS sources are considered to be young radio sources which evolve into large radio objects during their lifetimes. This interpretation of the CSS class has now become part of a standard model (Fanti et al., 1990, 1995, and Readhead et al., 1996) have proposed an evolutionary scheme unifying the three classes of sources: GPS, CSS and Large Symmetric Objects (LSOs).

Snellen et al. (1999) discussed many aspects of the evolutionary scheme presented above. In particular they concluded that the radio luminosities of GPS sources increase as they evolve, reach a maximum in the CSS phase and then gradually decrease as these objects grow further to become LSOs. In fact, LSOs are also divided into two distinct morphological groups of objects: FR Is and FR IIs (Fanaroff & Riley, 1974), and there is a relatively sharp luminosity boundary between them. The nature of the FR-division is still an open issue, just as are the details of the evolutionary process in which CSS sources become LSOs. It is unclear whether FR II objects evolve to become FR Is, or whether a division has already occurred amongst CSS sources and some of these then become FR Is and some FR IIs. A majority of CSS sources known to date have high radio luminosities and, if unbeamed, have FR II structures. It seems reasonable to suspect that some of the CSSs with lower radio luminosities could be the progenitors of less luminous FR I objects. According to a recently developed model by Kaiser & Best (2007), all sources start out with a FR II morphology. Some of them have weaker jets which disrupt within the dense environment of their host galaxies and develop the turbulent lobes of FR Is or become hybrid objects (Gawroński et al., 2006). Gopal-Krishna & Wiita (2000). In the model of Alexander (2000), sources with disrupted jets fade away.

The above considerations touch another aspect of the theory of evolution of radio-loud AGNs. It has already been pointed out by some authors (Gugliucci et al., 2005; Kunert-Bajraszewska et al., 2006; Marecki et al., 2003; Snellen et al., 1999) that there exists a group of GPS/CSS sources that will never reach the LSO stage, at least in a given cycle of activity if it is recurrent. Radio galaxies that are no longer fuelled and so remain in a coasting phase are sometimes termed ‘faders’ and so there is no reason why a class of small-scale objects that resemble large-scale faders should not exist. Strong support for this idea comes from Reynolds & Begelman (1997) who proposed a model in which extragalactic radio sources are intermittent on timescales of $\sim 10^5$–$10^6$ years. This scenario conforms to earlier predictions that Compact Symmetric Objects (CSOs) could switch off after a short period of time (Readhead et al., 1994). It also solves another well-known problem namely that the number of compact sources is too high relative to the general population of radio galaxies (Fanti et al., 1990; O’Dea & Baum, 1997).

Recent observations of weaker compact sources have shown that young FR Is (Giroletti et al., 2005) and small-scale faders (Kunert-Bajraszewska et al., 2005, 2006; Marecki et al., 2006) do indeed exist.
also revealed the existence of more exotic objects which
are relics of young sources that has been largely neglected to date. The goal of this project is to study the properties of LLC objects and the evolution of the compact object population.

The following criteria were used for the selection of candidates which were weaker CSS sources.

- Using the final release of FIRST, combined with the GB6 4.85 GHz survey, unresolved and isolated objects i.e. more compact than the FIRST beam (5″) and surrounded by an empty field (field radius 1″) were identified.
- The redshifts of the sources, which were identified with the radio objects, had to be known. These were extracted from NED and SDSS/DR4. Consequently, thus providing a low luminosity criterion: $L_{1.4\text{GHz}} < 10^{26}$ W Hz$^{-1}$.
- The flux density was chosen to be in the range 70 mJy ≤ $S_{1.4\text{GHz}} ≤ 1$ Jy in order to produce a sample of manageable size, but also to exclude objects with flux densities too low to be detected in a snapshot observations.
- We established the steepness criterion: $\alpha_{1.4\text{GHz}} > 0.7 \ (S \propto \nu^{-\alpha})$.

There is no overlap between the new sample and our previous one (Kunert et al., 2002). Finally, the new sample consists of 44 sources.

The initial survey was undertaken using MERLIN at 1.6 GHz. Snapshot observations of the sample were made on seven separate days between December 2006 and May 2007. Each target source together with its associated phase reference sources was observed for ~60 min including telescope drive times. The phase calibrator sources were observed twice per target scan for 1-2 min. Initial amplitude calibration was derived from daily observations of the unresolved source OQ208. The preliminary data reduction was made using an AIPS-based PIPELINE procedure developed at JBO. The resulting phase-calibrated images created with

Table 1  Morphological classification of the sources based on the described observations. Objects with uncertain classification are denoted with “?”.

| Type          | Sources                                      |
|---------------|---------------------------------------------|
| Single        | 0754+401, 0801+437, 0835+373, 0907+049, 0914+114, 0921+143, 1359+525A, 1402+415, 1407+363, 1411+553, 1418+053, 1521+324, 1532+303, 1717+547 |
| Core-jet      | 0025+006(?), 0846+017, 0931+033, 1009+053, **1140+058** , 1506+345A, 1601+528, 1610+407 |
| Double-lobed  | 0810+077, 0821+321, 0850+024, 0851+024, 0914+504A, **0942+355** , 1007+142, 1037+302, 1053+505, 1154+435A, 1308+451, 1321+045(?), 1542+390, 1543+465, 1558+536A, 1624+049, 1715+499 |
| Other         | **0854+210**, 0923+079, **1156+470**, **1550+444**, 1641+320 |

Fig. 1  Luminosity-size diagram from Akujor & Garrington (1995) for the revised 3C sample of Laing et al. (1983). Squares indicate CSS sources, filled circles indicate FR II objects, open circles indicate FR I sources. The boundaries of the latest samples of CSS sources are also shown: the dashed line indicates Fanti et al. (2001) sample, the dotted line indicates Kunert et al. (2002) sample and the solid line indicates the current sample of LLC sources.

2 Previous observations and new sample

Using an early release of the VLA FIRST survey (White et al., 1997, Marecki et al., 2003) selected a flux density limited, complete sample of 60 candidate sources fulfilling the basic criteria of the CSS class. The sample was initially observed with MERLIN C-band, after which selected groups of objects were further observed with MERLIN, the EVN and the VLBA (Kunert et al., 2002, Kunert-Bajraszewska et al., 2005, 2006, 2007, Marecki et al., 2003, Marecki et al., 2006). While a number of sources in the sample were shown to have morphologies similar to the strong, more ‘classic’ CSS sources (two symmetric edge-brightened lobes with well defined hotspots, or core-jet morphology), the observations also revealed the existence of more exotic objects which were strong candidates for compact faders. A double source, 0809+404, described in Kunert-Bajraszewska et al. (2006) was the best example of such an object. The VLBA multi-frequency observations showed it to have a diffuse, amorphous structure, devoid of a dominant core and hotspots.

Most of the GPS/CSS sources known to date are powerful objects with a FR II radio morphology. This is a result of a selection effect, since the main criterion used so far was flux density and not luminosity. A next step in studies of GPS and CSS objects is the observation of compact objects with moderate and low luminosities. It is assumed that amongst them there exists a class of objects which are relics of the VLBA (Kunert et al., 2002; Kunert-Bajraszewska et al., 2006) and the EVN (Marecki et al., 2003; Marecki et al., 2006).
Fig. 2  MERLIN L-band images of four sources from our new sample. The selected objects are indicated with bold type in Table 1. Contours increase by a factor 2, and the first contour level corresponds to ≈ 3σ. A cross indicates the position of an optical object found using the SDSS/DR6.

PIPELINE were further improved using several cycles of self-calibration and imaging, the final maps being produced using IMAGR.

Throughout the paper, we assume a cosmology with $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$.

3 Preliminary results

The selection criteria used for the new sample of candidate CSS sources means that objects with low luminosities that have previously never been observed so widely, have been selected. This is shown on the luminosity-size diagram (Fig. 1), originally derived by Akujor & Garrington (1995) for the revised 3C sample by Laing et al. (1983). Now indicated are the samples of Fanti et al. (2001), Kunert et al. (2002) and the present sample. The 178 MHz flux densities of sources have been estimated for the three samples using the known spectral indices between 0.4-1.4 GHz (Fanti et al., 2001) and 1.4-4.9 GHz (Kunert et al., 2002, new sample) and assuming that the indices remain valid down to 178 MHz. This assumption may not always be true, but it is sufficient to show the boundaries of the above-mentioned samples. Approximately one third of the CSS sources from the new sample have a value for the 178 MHz luminosity lower than the luminosity boundary found for FR sources (Fanaro & Riley, 1974), which means that they are compact young sources with luminosities comparable to FR Is.

About 70% of the sources from the sample are galaxies and all of them are nearby objects with redshifts, $z$, less than 1, and linear sizes less than 15 kpc; i.e. typical for CSS objects. Based upon preliminary radio images at 1.6 GHz, the new sources have been divided into four categories (Table 1). 'Single' means the source is a pointlike object unresolved with MERLIN at the observed frequency. 'Core-jet' is a source with a bright central component and a one- or two-sided jet. 'Double-lobed' objects show at least two
kinds of morphologies. Some of them are compact doubles
without a visible radio core at 1.6 GHz, whereas the others
show a central weak component and distorted extended
structure. Most of the double objects also show brightness
asymmetry. The last category, 'other', comprises five sour-
ces with peculiar morphologies: two objects are binary sys-
tems with distorted radio morphologies, the other three have
only a single visible lobe. Fig. 2 shows example sources
from each category except those which are unresolved.

The large percentage of double objects with an asym-
nmetric morphology in the new sample confirms a previous
finding for the CSS source population. Subrahmanyan et al. (2001)
have shown that, as a class, the CSSs are more asymmetric
than larger radio sources of similar power. There are at least
two explanations of this observational fact. There is a high
probability that CSS sources interact with an asymmetric
medium in the central regions of the host elliptical galaxy.

Another explanation is the light-travel time effect, i.e.
the time lag between the images of the lobes as the observer
perceives them (Owsianik et al. 1998). It could be that the
far side of a source is being viewed at an earlier time than
the near side and that for some double asymmetric sources,
the near side hotspot can be seen at a time when it is be-
ing supplied by jet material, whereas the far side kpc-scale
hotspot isn’t. Hotspots not being supplied by jet material
fade very fast because electrons diffuse to regions of lower
density and magnetic field and consequently radiate inef-
ciently. As a result, such a source may be detected as a
single-lobed object, similar to the three already found in the
new sample (Fig. 2). This kind of objects have been already
observed in our previous sample (Marecki et al. 2003), and
amongst large-scale sources (Subrahmanyan et al. 2003).

According to earlier (Alexander 2000) and recent (Kaiser
& Best 2007) theoretical predictions the distorted structure of a source
arises when it tries to escape from the core radius of its host
galaxy. Those sources that survive their evolution through
the densest inner regions of their galactic atmosphere should
appear on the smallest scales as classical double (FR II type)
objects. Sources that are disrupted are likely to have a dif-
f erent morphology. In the model of Kaiser & Best (2007) they
become FR I sources or hybrid objects. However, Alexander
(2000) shows that sources with disrupted jets are not ex-
pected to evolve into FR I objects, but fade so strongly that
they become virtually undetectable. It is possible that some
of the sources from this new sample, namely 'single-lobed'
objects, are in a coasting phase now.

4 Conclusions and future plans

We have presented some of the results from MERLIN L-
band observations of a new sample of low luminosity com-
pact sources, the details of which will be discussed in a sepa-
rate paper.

We have also obtained new polarisation data and MER-
LIN C-band observations of some of the sources, which
should help to explain the asymmetry of the radio struc-
ture seen in some of them. Since most of the sources have
known spectra, it is hoped that further analysis will lead to
evidence for a lack of activity or interaction with the sur-
rounding medium. The results of this will also be presented
in a forthcoming paper.

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