Young Radio Sources

By CARLA FANTI[1]

[1] Dipartimento di Fisica, Università di Bologna – Via Irnerio 46, I–40126 Bologna,Italy

I review briefly the evidence for *youth* in CSSs/GPSs, the evolutionary models and their application to the data. Possible strategies to search for the youngest sources are also presented.

1. Introduction

Compact **S**teep–spectrum **S**ources (CSSs) are powerful extragalactic radio sources with their radio emission confined well within their host galaxy ($\lesssim$ 15kpc) and yet with a steep radio spectrum ($\alpha > 0.5, S \propto \nu^{-\alpha}$). Hence, they have physical scales tens to thousands of times smaller than FRIIs, although being of comparable radio power. Those CSSs whose spectrum peaks at about 1 GHz, are named **G**Hz **P**eaked **S**ources (GPSs). Terms like CSO, MSO indicate different sub–classes of CSSs, and refer to those **O**bjects displaying a two sided (or **S**ymmetric) emission and are either **C**ompact (< 1 kpc, $CSOs$) or **M**edium sized ($MSOs$), while $LSOs$ indicate the powerful **L**arge–sized **S**ymmetric **O**bjects, typically FRIIs.

Several, more or less complete, samples of such sources have been or are being studied at VLBI resolution (e.g. Fanti et al. 1990 [$3CR\&PW$]; Readhead et al. 1996a; Stanghellini et al. 1998; Polatidis et al. 1999 and Snellen et al. 1998)

For the properties of CSSs in the radio and at other wavelengths, I refer to the extended and comprehensive review by O'Dea (1998). I'll only pinpoint that observed low polarization, high rotation measures, conspicuous distortions in their radio morphology, etc. are easily understood (independent of the reason for why CSSs are small) in the framework of CSSs developing in the Interstellar Medium (ISM) of the host optical object, in contrast to large FRIs and FRIIs which live in the much more tenuous environment of the Intracluster Medium.

The only result I'll mention, since it is relevant to this presentation, is the good anti–correlation between the source linear size, LS, and the restframe turnover frequency in the radio spectrum (ν_m^{rest}). It extends over four order of magnitudes in LS and is well represented by the law $\nu_m^{rest} \propto (LS)^{-0.65}$. Such a turnover in the radio spectrum could be attributed to either Synchrotron Self–Absorption (SSA) or Free–Free Absorption (FFA), but, although there are no direct proofs so far in favour of either mechanism, for a number of reasons many people favour SSA. This mechanism does predict a similar correlation but between *component* size and ν_m. However, if the component size is proportional to some power of the source LS it is possible to justify the above anti–correlation. Note however, that this linear correlation does not necessarily represent an evolutionary track. Plausible evolution models (Sect. 2) imply that the source luminosity decreases as it ages and grows in size, according to $P \propto (LS)^{-h}$. It is easy to show that, in this case, a source will indeed move from the top left corner down to the bottom right corner of the correlation but along a line steeper ($\nu_m^{rest} \propto (LS)^{-0.92}, h = 0.5$, sect. 4) than the best–fit.

What are CSSs?? From the very beginning (Phillips & Mutel, 1982), the simplest interpretation for the nature of these objects was that they are young (*the youth scenario*). The problem in this case is that their number relative to the general radio source population, at first sight, is expected to be proportional to the age ratio. Namely CSSs were naively expected to be a minority while instead they are a large fraction ($\approx 15-25$ %) of the family of powerful radio source (see Fig. 12 in Fanti et al. 1990).

In order to avoid this "population problem", for many years people have worked at the hypothesis that CSSs/GPSs are as old as the large size radio sources, but embedded in an ISM dense enough to impede the radio lobes to drill through and escape from the host galaxy (*frustration scenario*, van Breugel et al. 1984). No compelling proof has been found so far to support this model (e.g. O'Dea 1998; Fanti et al. 2000) so I shall not discuss this point any further.

2. A simple ram–pressure model for radio source evolution

I now recall the relevant points of simple models for the *youth* scenario discussed e.g. by Fanti et al. (1995); Readhead et al. (1996b) and O'Dea & Baum (1997).

In this model the advance speed of the lobes, v_l, is governed by the equilibrium between the internal pressure, p_i, estimated by assuming minimum energy conditions (which seems plausible, see Sect. 3.2) and the ram pressure. If we express p_i as a function of the energy flux F_e carried by the jet (assumed relativistic) we get $p_i = (F_e/c) \times \Omega D^{-2} \approx n_{ext} m_p v_l^2$ where Ω is the solid opening angle of a conical jet, $D \approx (LS)/2$ the distance from the core of the impact region, n_{ext} the external medium particle density and m_p the proton mass. If the external density goes as $n_{ext} \approx n_0 (r_c/D)^\beta$ $\quad(\beta \approx 0$ for $D < r_c)$ we get:

$$v_l \approx \left(\frac{F_e \Omega}{n_0 r_c^\beta m_p c}\right)^{0.5} D^{(\beta-2)/2} \propto D^x$$

This expression can change slightly in more sophisticated models (e.g. Begelman 1996; Kaiser & Alexander 1997; Sect. 4 and Tab. 2).

With the above gas distribution we expect $v_l \propto D^{-1}$ up to r_c ($\beta \approx 0$) and $v_l \propto D^x$ beyond, (with x depending on the adopted model). For $\beta = 2$ the lobe velocity would be constant and it would be slowly decreasing for $\beta = 1.5$. For $n_0 \approx 0.1$ cm^{-3} and $r_c = 2$ kpc, a typical MSO would take $\approx 1.5 \times 10^6$ years to attain the size $LS \approx$10 kpc and a typical CSO, 100 pc in size, $\approx$400 years. So no difficulty for the *youth* model, except for the "population problem" mentioned in the introduction.

A way out of this difficulty is to assume that during its evolution, the radio source expansion velocity increases (it spends a shorter time at large sizes) or that its luminosity changes as some power of the size (Fanti et al. 1995; Readhead et al. 1996b and O'Dea & Baum 1997). Indeed, if we assume that in a radio source the luminosity P decreases as the linear size increases, then CSSs will evolve into weaker, more numerous, large size sources. This means that the $LSOs$ we count now at a given P in a catalogue, when they were CSSs they were much more powerful, and then less numerous than the CSSs with the same P present in the sample. In other words the size distribution should be examined not at a constant P, but along evolution lines in the $P - LS$ plane.

Let's assume therefore that the "population problem" can be overcome if $P \propto (LS)^{-h}$ and/or $v_l \propto (LS)^x$ and make use of the observed diameter and luminosity distributions. These distributions can be well fitted with power laws: $dN(LS)/d(LS) \propto (LS)^{-m}$ and $dN(P)/dP \propto P^{-b}$. Then, following e.g. Fanti et al. (1995), we can derive the following relationship between the components m, h, x and b:

$$m = hb + x \tag{2.1}$$

The quantities m and b can constrain the evolutionary parameters h and x. In addition,

TABLE 1. *CSOs* with measured lobe proper motions

Object	z	LS pc	μ μas/y	v_{sep} c	Age y	Ref.
0108+388	0.669	22.2	9.27	0.196	367	Owsianik et al. 1998, Polatidis et al. 1999
			11	0.24	310	Taylor et al. 2000
0710+439	0.518	87.1	15.538	0.251	1100	Owsianik & Conway 1998, Polatidis et al. 1999
			14	0.52	550	Taylor et al. 2000
0711+356	1.62	32		<0.4	> 250	Conway et al. 1994
1031+567	0.4597	32.1	14.6	0.62	620	Taylor et al. 2000
OQ208	0.0766	7	(66)	0.208	103	Stanghellini et al. 2000
1943+546	0.263	105	41.5	0.419	800	Polatidis et al. 1999
1946+708	0.101	40	(< 46)	<0.8	>200	Taylor & Vermeulen 1997
2021+614	0.2266	30	14.9	0.14	380	Tschager et al. 2000, Conway et al. 1994
2352+495	0.238	117	21.062	0.202	1900	Owsianik et al. 1999, Polatidis et al. 1999
			33	0.32	1200	Taylor et al. 2000

some models relate h and x to the behaviour of the external gas density, i.e. to the parameter β above. I'll go back to this point in Sect. 4.

3. Evidence for youth in CSSs: source age estimates

An obvious way to test the *youth* model is to determine the source age directly.

3.1. *Lobe proper motions*

So far, lobe proper motions have been measured in a handful of the smallest *CSOs* by several authors (Table 1). Note that I report the speed of separation of the two lobes, and hence $v_{sep} \approx 2 \times v_l$. From v_{sep} and LS the source age is immediately derived.

Measures obtained by different authors sometimes disagree, however, in spite of the uncertainties on the exact values of the separation speed, these data prove that at least *some CSOs* are indeed young.

No measurements of this kind exist so far for larger sources and there is little hope that such data will become ever available, since, in order to detect proper motions of the order of tens of μas/yr, resolutions of 1 mas or better are required. It is generally impossible to map with such small beams hotspots some tenths of mas in size, as are those in objects more extended than the *CSOs* of Table 1.

3.2. *Radiative ages*

Murgia et al. (1999) have fitted the integrated spectra of the CSSs in the 3*CR*&*PW* sample with a continuous injection synchrotron model. The model fits the data remarkably well from ~ 0.1 to ~ 200 GHz. Assuming equipartition magnetic field ($H_{\rm eq}$), the high frequency spectral break ($\nu_{\rm br}$) provides the radiative ages ($\tau_{\rm syn}$) of these radio sources.

These ages are a good estimate of the source age only when the source spectrum is dominated by the lobes, which have accumulated the electrons produced during the whole source lifetime. Indeed, in the lobe dominated sources of the sample there is a good inverse correlation between LS and $\nu_{\rm br}$: the larger is a CSS the longer is its (radiative) age. The estimated ages are $\approx (1 \div 100) \times 10^3$ years and the average expansion speed, $LS/\tau_{\rm syn} = (0.34 \pm 0.07)c$, not far from that found for *CSOs*. An interesting by-product of this analysis is therefore that the source magnetic field seems to be close to equipartition.

TABLE 2. Evolution Models

Model	x	h_{lobe}	$h_{h.spot}$
SB (con. jet)	$\frac{\beta-2}{2}$	$\frac{11\beta-14}{16}$	0.5
SB (cyl. jet)	$\frac{\beta}{2}$	$\frac{7\beta-4}{16}$	0.0
Be and $K\&A$	$\frac{\beta-2}{3}$	$\frac{7\beta-8}{12}$	$\frac{\beta+4}{12}$

$v_l \propto (LS)^x, P \propto (LS)^{-h}$

Particularly interesting is the case of 1943+546, where $\tau_{\rm syn}$ is remarkably close (Murgia, priv. comm.) to the kinematic age obtained by Polatidis et al. (1999). So, it seems that we can be confident that $H_{\rm eq}$ is a fair estimate for the magnetic field.

4. Evolutionary models and the data

In table 2, I give the dependence on β of x and h (Sect. 2) for the Scheuer/Baldwin (Scheuer 1974; Baldwin et al. 1982) model (SB) that we used (Fanti et al. 1995), and for the model by Begelman (1996) (Be). The model by Kaiser & Alexander (1997), ($K\&A$) gives the same relations as Begelman.

Note that: The Be model does not differ much from the SB conical jet model; both models converge to similar values for $\beta \approx 2$. The lobe speed is always decreasing with LS (or constant, $x \leq 0$) in the Be and SB conical jet models, unless the external gas density has a very steep gradient ($\beta > 2$). In the SB cylindrical jet model, instead, the lobe speed is always increasing with the source size, for $\beta \neq 0$. In all models the lobe luminosity increases ($h < 0$) with LS until $\beta \lessapprox 1.2$, then it starts decreasing while the hot–spot luminosity always is decreasing with LS ($h > 0$), although slowly.

The observed linear size and radio luminosity distributions for the $3CR\&PW$ sample give $m \approx 0.6 \pm 0.1$ (down to $LS \approx 0.3$ kpc) and $b \approx 1.3 \pm 0.2$. Entering these values into eq. (2.1) along with the dependence on β of x and h (Table. 2) we estimate $\beta \approx 2 \pm 0.1$ for both the SB conical jet and Be models. This value would indicate that the lobes of the CSSs in the $3CR\&PW$ sample are already out of the region where the gas density rapidly decreases with distance, i.e. out of the core radius. The lobe luminosity is predicted to decrease as $P \propto (LS)^{-0.5}$ and their speed is expected to be roughly constant.

We may expect that, going to smaller and smaller linear sizes, we reach the stage where the sources are still within the core radius, where $\beta \approx 0$. In this case, eq. (2.1) can be used to predict, from the models of Table 2, the value m in the LS distribution. The models predict an increase with LS of the source luminosity, a decrease of the advance speed and $m \approx -1.2 \div -2$. Such a range of values for m implies a strong drop in the number of sources of small diameter, in contrast with what is observed in the Stanghellini et al. (1998) and Snellen et al. (1998) samples, where instead $m \approx 0.7$.

A way to overcome the problem is to say that either the gas density never flattens as we approach the galaxy nucleus, or that at small sizes the source luminosity becomes dominated by the hot–spot luminosity, always increasing with decreasing size ($h \geq 0$,

Tab. 2). The models, however, predict a trend in hot–spot luminosity which is not fast enough (values of $h \gtrsim 1$ would be required). So additional assumptions are required to fit the observed data.

5. Towards infant sources

The first announced discovery of sources peaking at very high frequencies came from Edge et al. (1996) who found two radio sources, peaking at 20 and 30 GHz respectively. According to the $LS - \nu_m$ relation these objects could be very small and hence young.

Following this report Dallacasa et al. (submitted) undertook a systematic search for such objects, nicknamed **H**igh **F**requency **P**eakers (HFP). All their HFP candidates were observed with the VLA simultaneously in 5 different bands from 1.4 to 22.5 GHz, and, out of the original list, 43 resulted "genuine" $HFPs$, with $S_{5\mathrm{GHz}} > 300$ mJy.

The observed median $< \nu_m >$ of the turnover frequency is ≈ 6.5 GHz, $\approx$5 times higher than in Stanghellini et al. (1998) and Snellen et al. (1998). Fifteen objects $(35 \pm 10)\%$ peak above 10 GHz, 7 of which $(16 \pm 7)\%$ above the highest observed frequency (22 GHz). According to the $LS - \nu_m$ relation these objects are expected to be a few pc in size, and then, in the *youth* scenario, younger than 50–100 years. The results are encouraging, but the number of $HFPs$ is still too small to allow any statistical study.

The possibility of making large area surveys, at very high frequencies, unbiased for spectral selections would allow the systematic search for $HFPs$.

The only one I am aware of, is the serendipitous survey by Cooray et al. (1998) at 28.5 GHz (1 cm). It lists 64 radio sources down to $S \sim 0.4$ mJy, for 52 of which spectra, from literature data, can be computed. Of them 5 could be ordinary GPSs, but 5 other peak above 10 GHz, of which three have a spectrum still rising at 28.5 GHz. At face value one could say that half of the inverted spectrum sources in this survey are $HFPs$.

So, in spite of the small numbers, it seems that a very high frequency selection is even more efficient in finding infant sources.

6. Conclusions

The *youth* model seems to properly explain a number of observational data, but we are still quite far from having understood how radio sources were born and what they evolve into. We don't even know if the few measured lobe proper motions are exceptional events or if they are a "normal"phenomenon. The spectral study of Murgia et al. (1999), indicates that CSSs *are* young, on average, but direct measures of the separation speed are necessary to refine the source models, such as those reviewed in Sect. 4. Thus we should monitor as many objects as possible to determine their lobe speed (as a function of size and radio power) and to sample n_{ext}.

The selection in the recent years of samples of GPSs has been extremely useful since it has allowed us to map very small radio sources, focusing our attention on the young nature of these objects. But these samples are very much biased and are not the most appropriate to truly study the radio source evolution. They do not even tell us the true percentage of $CSOs$ in the radio source population.

What we would need is a large sample, unbiased for spectral turnover, and selected at frequencies so high ($>$ 100 GHz??) that we observe for certain the thin part of the spectrum, followed by simultaneous multi–frequency observations to define the spectral shape. In this way all, or most, of the range in peak frequencies (and hence in size and age) is explored. Complete mapping, optical identification and spectroscopy would then allow to determine the bivariate (size, power) luminosity function of such objects from which we might derive the time evolution of the radio sources.

Finally, there are several problems which require investigation. I just mention the two which I think are the most puzzling.
– Quasars in GPS (Stanghellini et al. 1998; Snellen et al. 1998) and HFP (sect. 5) samples are found at redshifts higher than galaxies: this seems to be in contradiction with AGN orientation–unified models
– In the *youth* model CSS/GPS which are $\approx$ 100 times smaller than LSO's of the same power, should have "radio engines" $\approx$10 times weaker. Since it has been claimed since Baum & Heckman (1989) that the radio jet energy is proportional to the bolometric luminosity of the AGN, we would expect young objects to be definitely less powerful in the MFIR and NL emission, contrary to what observed (Fanti et al. 2000; Morganti et al. 1997).

REFERENCES

Baldwin, I. 1982, In *IAU Symp. 97, Extragalactic Radio Sources* (ed. D.S. Heeschen and C.M. Wade) p.21. Reidel.

Begelman M.C. 1996, In *CygA: Study of a Radio Galaxy* (ed. C.Carilli & D.Harris) p. 209, Camb.Univ. press.

Baum, S.S., & Heckman, T. 1989, *ApJ* **336**, 702

Cooray, A.R., Grego, L., Holzapfel, W.L., et al. 1998, *AJ* **115**, 1388

Conway, J.E., Myers, S.T., Pearson, T.J., et al. 1994, *ApJ* **425**, 568

Edge, A.C., Jones, M., Saunders, R., et al. 1996, *The 2nd workshop on GPS and CSS radio sources* (ed. I.A.G. Snellen et al.) p. 43

Fanti, C., Fanti, R., Schilizzi, R.T., et al. 1990, *A&A* **231**, 346

Fanti, C., Fanti, R., Dallacasa, D., et al. 1995, *A&A* **302**, 317

Fanti, C., Pozzi, F., Fanti, R., et al. 2000, *A&A* **358**, 499

Kaiser, C.R. & Alexander, P. 1997, *MNRAS* **286**, 215

Morganti, R., Tadhunter, C.N., Dickson, R., et al. 1997, *A&A* **326**, 130

Murgia, M., Fanti, C., Fanti, R., et al. 1999, *A&A* **345**, 769

O'Dea, C.P. & Baum, S.A. 1997, *AJ* **113**, 148

O'Dea, C.P. 1998, *PASP* **110**, 493

Owsianik, I., Conway, J.E., Polatidis, A.G. 1998, *A&A* **336**, L37

Owsianik, & I., Conway, J.E. 1998, *A&A* **337**, 690

Owsianik, I., Conway, J.E., Polatidis, A.G. 2000, *NewAR* **34**, 669

Phillips, R.B. & Mutel, R.L. 1982, *A&A* **106**, 21

Polatidis, A., Wilkinson, P.N., Xu, W., et al. 1999, *NewAR* **34**, 657

Readhead, A.C. S., Taylor, G.B., Xu, W., et al. 1996a, *ApJ* **460**, 612

Readhead, A.C. S., Taylor, Pearson G.B., et al. 1996b, *ApJ* **460**, 634

Scheuer, P.A.G. 1974, *MNRAS* **166**, 513

Snellen, I.A.G., Schilizzi, R.T., De Bruyn , A.G., et al. 1998, *A&AS* **131**, 435

Stanghellini, C., O'Dea, C.P., Dallacasa, D., et al. 1998, *A&AS* **131**, 303

Stanghellini et al. 2000, *in these proceedings*

Taylor, G.B. & Vermeulen, R.C. 1997, *ApJL* **485**, L9

Taylor, G.B., Marr, J.M., Pearson, T.J., et al. , 2000, *ApJ* in press

Tschager et al. 2000, *A&A* in press

van Breugel, W.J.M., Heckman T., & Miley G.K. 1984, AJ **89**, 5