A dynamical model for the CSO-MSO-FRII evolution: hints from hot spot properties

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Abstract

Compact Symmetric Objects (CSOs) are considered the young counterparts of large doubles according to advance speeds measured or inferred from spectral ageing. Here we present a simple power law model for the CSO/FRII evolution based on the study of sources with well defined hot-spots. The luminosity of the hot spots is estimated under minimum energy conditions. The advance of the source is considered to proceed in ram pressure equilibrium with the ambient medium. Finally, we also assume that the jets feeding the hot spots are relativistic and have a time dependent power. Comparison with observational data allows to interpret the CSO-FRII evolution in terms of decreasing jet power with time.

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1 Introduction

Compact Symmetric Objects (CSOs) are thought to be early stages of powerful extended radio sources as first suggested by Phillips & Mutel (1982) and later worked out by Readhead et al. (1996). This view has been underpinned by recent measurements of hot spot advance speeds (Owsianik & Conway 1998, Owsianik et al. 1998, Taylor et al. 2000, Tschager et al. 2000, Polatidis et al. 2003) and spectral ageing measures (Murgia et al. 2003).

Current evolutionary models (see Fanti & Fanti 2002) relate luminosity and expansion velocity of a source to jet power and external gas density. The energy accumulated in the lobes drives the source expansion. Ram pressure equilibrium with the ambient medium is assumed. The volume of the source is usually inferred from self-similarity arguments whereas radio power is computed from equipartition assumptions. In all the models, jet power was considered as constant.
Here we discuss a model, presented in Perucho & Martí (2002a, Paper II), for the long term evolution of powerful radio sources, which is an extension to time dependent jet power of the model introduced in Perucho & Martí (2002b, Paper I) for CSOs. In order to avoid conjectures about the volume growth of the source (e.g., self-similarity), we concentrate in the study of the hot spots for which properties like size or luminosity can be derived reliably. In our model we assume that the advance work of the hot-spot is directly connected to the jet power. The remaining assumptions of our model are standard. The luminosity of the hot spots is estimated under minimum energy conditions. The advance of the hot spot proceeds in ram pressure equilibrium with the ambient medium. Finally, we also assume that the jets feeding the hot spots are relativistic.

In section 2, we give the main equations derived from the model. In section 3 we present the observational data we compared with our model, and section 4 is devoted to discussion and conclusions drawn from this work.

2 A dynamical model for the evolution of hot spots in powerful radio sources

Our model relies on three basic parameters. The first ($\beta$) is the exponent for the growth of linear size of a hot spot with time, $r_{hs} \propto t^\beta$ as it propagates through an external medium with density varying with linear size ($LS$) as $\rho_{\text{ext}} \propto (LS)^{-\delta}$, where $\delta$ is the second parameter.

Using the hot-spot advance speed, we can relate linear size with time and describe the evolution of physical parameters in terms of distance to the source of the jets feeding them. Considering that hot-spots advance with non-relativistic speeds, ram pressure equilibrium leads to,

$$v_{hs} = \sqrt{\frac{F_j}{A_{j,hs} \rho_{\text{ext}}}},$$  

(1)

where $F_j$ is the jet thrust and $A_{j,hs}$, the cross-sectional area of the jet at the hot spot, assumed to be $\propto r_{hs}^2$.

The final step is to consider that for a relativistic jet, jet thrust and power, $Q_j$, are simply related by $F_j \approx Q_j/c$. If we now allow for a dependence of the jet power with time like $Q_j \propto t^\varepsilon$ (where $\varepsilon$ is the third parameter), combine all the dependencies and integrate, we get

$$v_{hs} \propto (LS)^{\delta/2+\varepsilon/2-\beta} \rightarrow t \propto (LS)^{(1-\delta/2)/(\varepsilon/2+1-\beta)}.$$  

(2)

Substituting now in the expressions for the hot spot radius and speed, we obtain

$$r_{hs} \propto (LS)^{\beta(1-\delta/2)/(\varepsilon/2+1-\beta)}, \quad v_{hs} \propto (LS)^{(\delta/2+\varepsilon/2-\beta)/(\varepsilon/2+1-\beta)}.$$  

(3)

The next equation in our model comes from the source energy balance. We assume that the power consumed by the source in the hot spot advance, $(PdV)_{hs,\text{adv}}$ adjusts
to the evolution of the jet kinetic power, i.e.,

\[(PdV)_{\text{hs,adv}} \propto P_{\text{hs}} r_{\text{hs}}^2 v_{\text{hs}} \propto Q_j \propto t^\varepsilon.\]  

Finally, under the assumption of minimum energy, the luminosity of the hot-spot \((L_{\text{hs}} \propto P_{\text{hs}}^{7/4} r_{\text{hs}}^{3})\) may be expressed in terms of \(LS\)

\[L_{\text{hs}} \propto (LS)^{7/4(-\delta/2(\varepsilon-2\beta)+\varepsilon/2-\delta/2-\beta)+3\beta(1-\delta/2))/(\varepsilon/2-\beta+1).\]  

Inverting eqs. (3) and (5), we derive expressions for the evolution parameters of our model in terms of exponents for the evolution of observable quantities.

\[\beta = \frac{s_r}{1-s_v}, \quad \delta = \frac{12}{7}s_r - \frac{4}{7}s_L + s_v, \quad \varepsilon = \frac{2/7s_r + 4/7s_L + s_v}{1-s_v},\]  

where \(s_r\), \(s_v\) and \(s_L\) stand for the values of the exponents of the observed hot spot radius, advance velocity and luminosity as functions of \(LS\). Figure 1 shows the variation of \(\beta\) and Figure 2 that of \(\delta\) and \(\varepsilon\) with the different exponents. Let us note that the previous expressions not only provide a system of algebraic equations to obtain values for the theoretical parameters in our model. They also prove that our model is self-consistent since the variations of the theoretical parameters induced by those derived from observations agree with physical expectations. Therefore, if we are able to obtain values for the exponents in eqs. (3) and (5) from observational data assuming that the corresponding \(LS - L_{\text{hs}}\) and \(LS - r_{\text{hs}}\) plots track the evolution of individual sources, we can derive expected values for \(\beta\), \(\delta\) and \(\varepsilon\) from the observational fits.

3 Observables from hot spots

In order to apply our model to the evolution of powerful radio sources from the CSO to the FRII phases, we have compiled a sample of sources with linear sizes between

![Figure 1: Contours of \(\beta\) as function of \(s_v\) and \(s_r\) for the model discussed in the text. Boxes bound the expected values of \(\beta\) for CSO-MSO evolution (solid lines) and MSO-FRII evolution (dashed lines).](image-url)
tens of pcs to hundreds of kpcs and well defined hot spots. The sample of CSO is the same as the one used in Paper I. Sources were selected from the GPS samples of Stanghellini et al. (1997), Snellen et al. (1998, 2000) and Peck & Taylor (2000). We have chosen the sources with double morphology already classified in the literature as CSOs and also those whose components can be safely interpreted as hot spots even though the central core has not been identified yet. The criteria we have followed are quite similar to those used by Peck & Taylor (2000), although see Paper I for details.

Seven Medium size (1 - 10 kpc) symmetric objects (“doubles”) have been taken from the CSS-3CR sample of Fanti et al. (1985). Finally, 40 sources from the sample of FRII-3CR radio galaxies of Hardcastle et al. (1998) have been considered. See Paper II for further details.

All the subsamples in our combined sample have similar flux density cut-offs: 1 Jy at 5 GHz for the CSOs and 10 Jy at 178 MHz for the MSOs and FRIIs. The differences in redshift among the three subsamples (\( z \leq 1 \) for the CSOs; \( 0.3 < z < 1.6 \) for the MSOs; \( z < 0.3 \) for the FRIIs) enhances the luminosity drop between MSOs and FRIIs.

Figure 3 displays the hot spot radius and luminosity with respect to projected linear size on logarithmic scales, together with the best linear fit for both CSO-MSO and MSO-FRII subsamples. Hot-spot linear sizes and luminosities have been calculated as explained in the Appendix of Paper I. Table 1 compiles the slopes characterizing the power law fits and their errors, as well as the correlation coefficients.

4 Discussion

Assuming an evolutionary interpretation of the plots in Fig. 3, the most remarkable aspects of those plots are the self-similar growth of hot-spot radius with linear size for the first ten kpc of evolution and flattening for large sources, in agreement with
Figure 3: Log-log plot for the hot spot radius and luminosity versus projected linear size for the sources in the combined sample. Continuous lines correspond to the best linear fits for both CSO-MSO and MSO-FRII subsamples.

Table 1: Best fits for radius ($s_r$) and luminosity ($s_L$), along with their errors and correlation coefficients ($r$). In the right part of the table we write the values of the evolution parameters ($\beta$, $\delta$, and $\epsilon$) which result from the calculated best fits and two different possible slopes for advance speed ($s_v$), along with their errors, which are directly taken from Figs. 1,2 for $\beta$, $\delta$ and $\epsilon$.

|        | $r_{hs}$ | $s_r$  | $L_{hs}$ | $s_L$  | Model         | $\beta$ | $\delta$ | $\epsilon$ |
|--------|----------|--------|----------|--------|---------------|---------|----------|------------|
| CSO-MSO| 1.0 ± 0.3| 0.93   | 0.24 ± 0.14| 0.26  | $s_v = 0$    | 1.0 ± 0.3| 1.6 ± 0.6| 0.4 ± 0.2 |
|        |          |        |          |        | $s_v = -0.5$ | 0.7 ± 0.2| 1.1 ± 0.7| -0.05 ± 0.15|
| MSO-FRII| 0.40 ± 0.11| 0.51 | -1.32 ± 0.15| -0.69 | $s_v = 0$    | 0.4 ± 0.2| 1.4 ± 0.5| -0.6 ± 0.2 |
|        |          |        |          |        | $s_v = -0.2$ | 0.3 ± 0.2| 1.2 ± 0.5| -0.75 ± 0.15|

Jeyakumar & Saikia (2000), and the change of sign of the slope for radio-luminosity also at ten kpc. This fact is consistent with the transition between the ISM and the IGM, also suggested by the disappearance of IR aligned emission after the CSS stage (de Vries et al. 2003), which could imply significant changes in the evolution.

Fits can be used to constrain the parameters $\beta$, $\delta$, $\epsilon$ of the model. These values appear listed in Table 1. Hot spots undergo a secular deceleration (from $0.2c$ in the first kpc to a value $\approx$ ten times smaller in FRIIs) and there are no observational indications of any acceleration, hence constant and decreasing hot spots velocities have been considered for the CSO-MSO and MSO-FRII fits.

The break in the fits shown in Fig. 3 at 1-10 kpc produce very different values for the parameters in the CSO-MSO and MSO-FRII phases. On the contrary, there is a complete consistency between the fits for the CSOs alone (see Paper I) and those for the CSO-MSO phase. The hot spot expansion rate, $\beta$, decreases from $\approx 1$ in the CSO-MSO phase to $\approx 0.4$ in the MSO-FRII phase. Jet power increases with time during the first phase ($\epsilon \approx 0, 0.4$ depending on the value chosen for $s_v$) and decreases in the
long term ($\varepsilon \approx -0.6, -0.7$). It would be interesting to relate the time evolution of the jet power with the physical processes responsible for the jet production (i.e., accretion rate, black hole spin). The density profile is flat ($\delta < 2$), consistent for the CSO-MSO stage with that derived by Pihilstroem et al. (2003) ($\delta \approx 1.3$) for GPS-CSS sources from HI detections, and the transition between the two phases is smooth, although this can be a result of the fitting process that washes out any steep gradient between a flat ($\delta \approx 0$), small core and the intergalactic medium. We also note that the density gradient depends strongly on $s_v$ and that this parameter is poorly known. A value of $\delta = 2$ in the CSO-MSO phase will produce accelerating hot spots ($s_v = 0.5$) and a large increase of the jet power ($\varepsilon = 2$). Finally, fixing $s_L$ and $s_r$ and taking $\delta = 0$, we get $s_v = -1.5$, which is too small to be maintained over a long distance: starting with a hot spot speed of $0.2c$ at 50 pcs, the hot spot speed at 0.5 kpc would have decreased up to $6 \times 10^{-3}c$, much smaller than the present accepted values for CSO advance speeds (Polatidis et al. 2003, Murgia et al. 2003). It would be interesting to have upper limits of hot spots advance speeds in CSOs in order to constrain the density profile and the jet power evolution.

Regarding the problem of trapped sources, a suitable configuration of external medium density and jet power evolution may lead to a number of sources which, along with core-jets, may contribute to the excess of small sources in count statistics (Marecki et al. 2003, Drake et al. 2003).

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