Proceedings of the 6th European VLBI Network Symposium
Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)
June 25th-28th 2002, Bonn, Germany

Proper Motions in Compact Symmetric Objects

A. G. Polatidis[1], J. E. Conway[2], and I. Owsianik[1]

[1] Max Planck Institut für Radioastronomie, Postfach 2024, D-53010, Bonn, Germany
[2] Onsala Space Observatory, Chalmers Technical University, Onsala S-43992, Sweden

Abstract. This paper discusses recent measurements of proper motions of the hot spots of Compact Symmetric Objects. We review the evidence for lobe expansion of CSOs and its use as a methods to estimate their kinematic ages. New, refined values for the expansion velocity of hot spots are presented. The kinematic ages measured in 10 CSOs so far points to these objects being very young ($< 10^4$ years). For a few CSOs the ages have been estimated from methods used for the larger sources and agree with the kinematical ages. There is also increasing evidence that a minority of these objects are just the recent phases of recurrent emission.

1. Introduction

The study of powerful radio sources with VLBI surveys conducted during the past two decades, further from confirming the near ubiquity of objects exhibiting an asymmetric one–sided nuclear jet, (in agreement with the relativistic beaming model) has also demonstrated that the few hitherto known objects with double or triple structure at parsec scales (e.g. Conway et al. 1992) constitute a significant part of complete flux density limited samples; Wilkinson et al. (1994) gave the name "Compact Symmetric Objects" (CSOs) to this new class.

In CSOs radio emission regions are seen on both sides of the centre of activity, in the form of mini-lobes and/or jets on scales of 1 pc to 1 kpc. Hot spots, the "working surfaces" of the jets, are often found embedded in the lobes. The centre of activity, the core, has an inverted radio spectrum and, unlike the typical core-jet sources, does not dominate the radio emission at cm wavelengths; in fact sometimes the core may be located at the end of a bright jet (e.g. Taylor et al. 1996). Relativistic beaming is unlikely to play an important role in the lobes and hot spots of CSOs (Wilkinson et al. 1994). CSOs often have a radio spectrum which peaks around a few GHz and thus belong to the class of Gigahertz Peaked Spectrum (GPS) sources (for a review see O'Dea 1998).

In general, the CSOs have no larger-scale radio emission, though there is mounting evidence that in some of them very low luminosity extended emission exists (e.g. Owsianik et al. 1998, Stanghellini 2002). Morphologically the radio structure of the CSOs is similar to the large, kiloparsec and Megaparsec sized, double-sided radio sources (dubbed 'classical doubles'), only they are approximately 1000 times smaller. A striking example of such similarity is the $\sim 105h^{-1}$ pc (42 mas) large radio galaxy 1943+546 (figure 1, Polatidis et al. 1999)

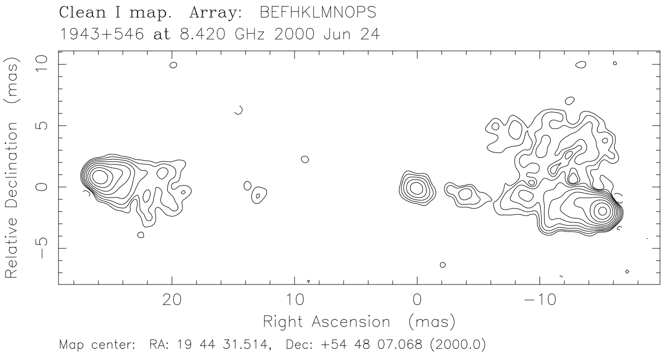

Fig. 1. Global VLBI image of 1943+546 at 8GHz. The restoring beam is 95 mas and the contour levels are -1,1,2,4,8,16,32,64,128,256,512 x 0.3 mJy/beam

The Compact Symmetric Objects comprise a significant fraction of sources in flux density limited samples at 5 GHz (Polatidis et al. 1999). For example, in the 200 sources, statistically complete sample of the combined Pearson and Readhead (1988) and the first Caltech–Jodrell Bank (CJ1) VLBI surveys (e.g. Polatidis et al. 1995), 7.5% (15 sources) are CSOs, 5% (10 sources), are Medium Symmetric Objects, (symmetric structures with sizes 1 kpc–15 kpc), and 34% (68 sources) are large (> 15kpc), lobe–dominated radio sources, with a Fanaroff-Riley type I or II morphology.

The nature of Compact Symmetric Objects has been discussed for many years. While soon after the detection of the first examples it was suggested (Philips & Mutel 1982) that they are young radio sources which would evolve into large radio sources, alternative suggestions have also been proposed: CSOs could be 'frustrated', ie. located in dense environment that could inhibit the growth of the radio structure. CSOs could also be young radio sources, that will 'fizzle' out and die young (Readhead et al. 1994) or just stages of intermittent radio activity (Reynolds & Begelman 1997).

2. Proper motions in CSOs

Since CSOs usually contain compact and bright components well separated from the underlying lower luminosity

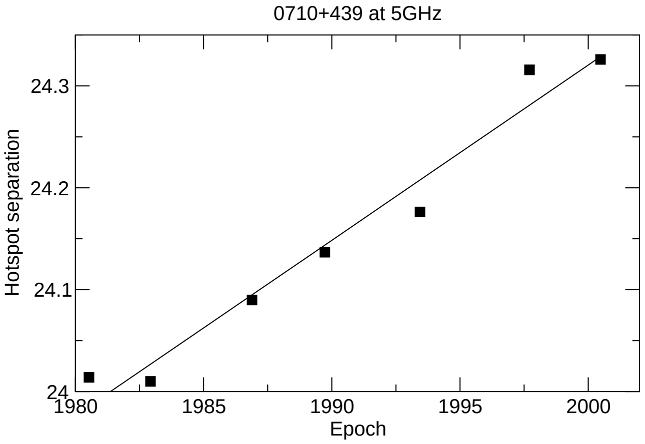

Fig. 2. Hot spot expansion of 0710+439 at 5GHz. Squares and straight line is the hot spot separation measurements and the least squares fit.

Table 1. Expansion Velocities and Kinematical ages of Compact Symmetric Objects

Source	z	Size^a	v^a_{sep}	Age	Nr. of Epochs	Ref^b
			Detections			
0035+227	0.096	27.03	0.123	703	2 (1998-2001)	1
0108+388	0.669	22.02	0.174	367	5 (1982-2000)	2
0710+439	0.518	86.8	0.292	950	7 (1980-2000)	3
1031+567	0.4597	109	0.6	600	2 (1995-1999)	4
1245+676	0.1071	14.4	0.163	282	5 (1989-2001)	5
OQ208	0.0766	7	0.1	224	6 (1993-2002)	6
1843+356	0.763	74	0.395	600	2 (1993-1997)	7
1943+456	0.263	105	0.262	1297	3 (1993-2000)	1
2021+614	0.227	16.1	0.120	440	3 (1982-1998)	8
2352+495	0.238	117	0.136	2752	6 (1983-2000)	9
			Limits			
1718-649	0.0142	2	0.07		2+	12
1934-638	0.183	85	0.05		3+	10
1946+708	0.101	80	0.100		2	11

^{a}: The Linear size and the hot spot separation velocities are reported in units of h^{-1}pc and h^{-1}pc for $H_o = 100h$ km s^{-1}Mpc^{-1}. ^{b}: 1. this paper, 2. Owsianik et al. (1998) and this paper, 3. Owsianik & Conway (1998) and this paper, 4. Taylor et al. (2000), 5. Marecki et al., in prep. and this paper, 6. Stanghellini et al. (2000), 7. Polatidis et al. (2001), 8. Tschager et al. (2000), 9. Owsianik et al. (2002), 10. Tzioumis et al. (1989) and priv. comm., 11. Taylor & Vermeulen (1997), 12. Tingay et al., priv. comm.

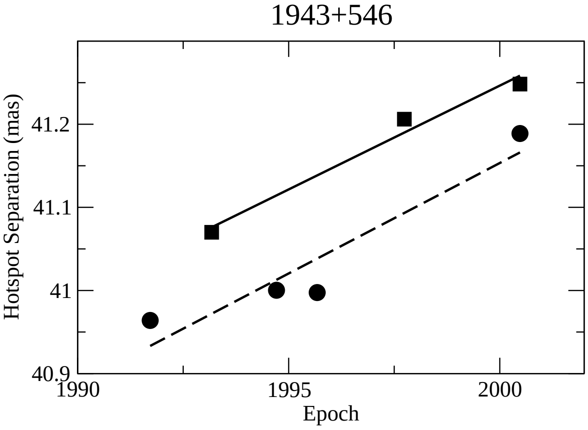

Fig. 3. Hot spot expansion of 1943+546: Squares and straight line is the hot spot separation and the least squares fit at 8GHz; circles and dashed line the hot spot separation and the least squares fit at 5GHz. The expansion velocities are similar.

emission, it is possible, using VLBI observations, to measure the component movements in them. Furthermore, due to their small size it is easy to infer changes of their size by directly measuring the relative separation rate of the compact hot spots. In contrast, in the larger kpc-size double radio sources, the hot spots are largely resolved with VLBI so no direct measurement of their relative separation, expected to be of the order of a few μas per year, is possible.

These hot spots are at, or very close to, the edges of the "mini-lobes", hence the total extent of the radio structure. This image is consistent with them being the working surface of the jets at it propagates through the ISM, and not just the location of a simple shock propagating in the jet, like those observed in knots of superluminal sources.

2.1. Hot Spot Expansion Velocities

The first upper limits to the expansion of the hot spots (Tzioumis et al 1989, Conway et al. 1994) showed that their velocities were sub-relativistic and hence much smaller than the core-jet objects.

The first unambiguous detections of CSO expansion were reported in the CSOs 0710+439 (Owsianik & Conway 1998, OC98) and 0108+388 (Owsianik et al. 1998, OCP98) based on multi-epoch VLBI observations over a decade or more. Since then, expansion or an upper limit to it has been detected in thirteen CSOs (Table 1). The velocity of hot spot expansion in all sources is between $0.1h^{-1}\,c$ and $0.395h^{-1}\,c$, the mean value being $0.23h^{-1}\,c$ (the velocity of 1031+567 is based on motion between a knot in the jet and the opposing hot spot, thus it can not be compared with the remaining sources. It is however evidence for expansion in the source).

Measurements of the hot spot expansion velocities in Table 1 have been made at different frequencies; usually at 5 GHz (e.g. Owsianik et al 1998, 2002; Tschager et al. 2000), at 8.4 GHz (e.g Polatidis et al. 1999 and this paper) or 15 GHz (e.g. Taylor et al 2000, TMP00).

Temporal coverage is also important so monitoring of CSOs continues through a number of years (Table 1 shows the number of epochs and the temporal coverage of the sources so far). In the sources 0710+439 (OC98), 0108+388 (OCP98) and 2352+495 (Owsianik et al 2002, OPC02), our λ6 cm VLBI observations cover by now almost 20 years and consist of 5-7 measurements (epochs) per source, thus allowing meaningful regression analysis (Figure 2 shows the change in the hot spot separation in

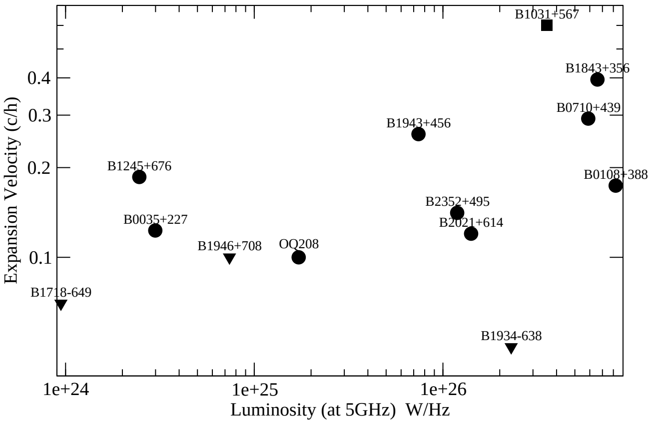

Fig. 4. Hot spot expansion velocity vs. source luminosity at 5 GHz. Filled circles are the sources with confirmed velocities and triangles are the sources with an upper limit to their expansion. (1031+567 is noted with a square - see text)

CSO 0710+439 between 1980 and 2000). This multi-epoch analysis adds further credibility to the measurements obtained from comparing only two epochs.

One notices however slight differences in the reported velocities in the literature as more epochs are added. This is possibly a combination of effects. First a purely observational one: “faster” velocities tend to be noticed, and reported first. Furthermore, averaging out of small temporal changes in the instantaneous velocity, gives a more representative value of the average velocity over the source age.

Where the same sources have been monitored at different frequencies, the derived velocities are usually similar. For example, for the CSO 1943+456 we report an expansion velocity (figure 3), from three epoch (1993.1–2000.4) measurements at 8.4 GHz, of $v_{\rm sep} = 0.262 \pm 0.039 h^{-1}$c which is within the errors with that independently derived using four epoch (1991.7–2000.4) 5GHz VLBI observations ($v_{\rm sep} = 0.279 \pm 0.063 h^{-1}$c). In the case of 2352+495 TMP00 report (based on two epoch 15GHz observations) a velocity twice as large as the one reported by OPC02 based at five epochs at 5GHz. A value similar to TMP00’s is noted at 8.4GHz (Polatidis et al., in prep.) from similar epochs, and also using only the similar epochs at 5GHz. This could be attributed to temporal variations in hot spot expansion velocities.

There is also evidence of differences in the apparent advance velocities of individual hot spots, particularly in the cases where we can reliably measure the motion of each hot spot with respect to the core. For example in 1943+546 the western hot spot is moving with a velocity of $0.107 h^{-1}$c, while the eastern (and farthest) hot spot moves away from the core with v_{hot}=$0.247 h^{-1}$c. Similar behaviour is seen in a few other sources where the core is identified (e.g. 0710+439, OC98). The difference in the velocities could reflect differences in the physical conditions of the hot spots as well as their environment. The different velocities are consistent with differences in the hot spot pressures in the same source of order 5 (e,g, Readhead et al. 1996 (RPX96), OC98). Furthermore, similar to 1943+546 where the slow hot spot is at the side of the larger lobe, hydrodynamic simulations (e.g. Bicknell et al., 2002) predict that a stronger interaction between the jet and denser ISM clouds, would deflect and diffuse the jet power, causing the lobe to inflate as well as the hot spot to slow down.

2.2. Interpretation

Before interpreting the hot spot expansion velocities, we should consider whether they are indeed representative of the growth rate of the source.

Random brightening and dimming of blended components would also move their centroids around, but the fact that in all cases we see outward motions argues against this. Hence what we measure are the hot spot separation changes averaged over a decade or so.

It is conceivable that CSOs would expand in rare brief bursts when encountering relatively low density medium, their advance being hindered by jet-cloud interactions during the rest of the time. Then we would be measuring only the velocity of these brief expansion periods and not the average expansion velocity over the lifetime of the source, hence severely overestimating their age. This is high unlikely given that we have measured expansion speeds in a very high fraction of the sources where this is possible (10 out of 13 cases, Table 1). Furthermore, in the framework of the ’dentist’s drill’ model (Scheuer 1982) the hot spot would move around much faster than the lobe advances. However, in most cases where a measurement was possible, the side-to-side motions of the hot spots were negligible compared to the outward motion (e.g OPC02, Polatidis et al., in prep.), and in 0108+388 (Owsianik & Tschager, priv. com.) the relatively larger hot spot movement normal to the separation vector, is much smaller than the outward expansion.

In any case it is clear that the *mean forward* advance speed of the hot spot must equal the *mean forward* advance speed of the lobe (if the hot spots were moving much faster, they would appear dissociated from the lobes).

2.3. The age of CSOs

One obvious application of the rate of expansion measurement in CSOs is, using their measured linear size, the determination of their kinematic age. *This constitutes so far the most direct way to estimate the age of an extragalactic radio source.* Source ages between 200-2800 years have been estimated for the CSOs in Table 1 (Column 5).

Furthermore, given the morphological similarity with the large ’classical double’ radio sources, it is possible to obtain age estimates of CSOs by applying the methods that have been used to determine the ages of ’classical doubles’ (see Conway 2002 for more details).

Readhead et al. (1996) applied the classical ’waste energy basket’ argument to CSO 2352+495. Comparing the jet's mechanical luminosity with the hot spot radio luminosity, it was obvious that most of the supplied energy was stored in the lobes. Assuming then minimum energy condition, they estimated an age of 3000 years for 2352+495, which is similar to the kinematical age of 2752 years (OPC02).

There have been attempts to estimate the age of CSOs and the larger double sources (MSOs) via the detection of high frequency breaks in their spectra due to ageing of the electrons in the lobes. Minimum energy and equipartition conditions are also assumed, but it is found that the spectral breaks in the lobes all occur above 1 GHz. The estimated spectral ages (eg. RPX96, Murgia et al. 1999) are $10^3 - 10^4$ years, similar to the kinematic ages. In fact Murgia (2002) derives a spectral age of ∼900 years for 1943+546, very close to the kinematic age of 1297 years.

3. 1245+676: a double-double radio galaxy

The z=0.107 radio galaxy 1245+676 is an extreme example of a 'double-double' radio galaxy. Its triple radio morphology (1.9 Mpc in extent, Lara et al. 2001) and radio luminosity is typical of an FR II galaxy baring the fact that the central component dominates the flux density (∼67% at 1.4 GHz, Lara et al. 2001) and hence the total radio spectrum, and is similar to the GPS sources. At parsec scale resolution, the core appears as a Compact Symmetric Object. Its 14.4 parsec structure is dominated by two mini-lobes containing hot spots; a slightly flatter spectrum component, located closer to the southern hot spot is tentatively identified with the core.

VLBI observations at 5GHz between 1989.7 and 2001.5 have shown that the hot spots move apart with a velocity of $0.163h^{-1}$c (Marecki et al., in prep.). This implies a kinematic age of 282 years for the core region. 1245+676 is by far the best example where a CSO is the youngest phase of recurrent radio activity, source hinting that at least some CSOs maybe re-born radio sources.

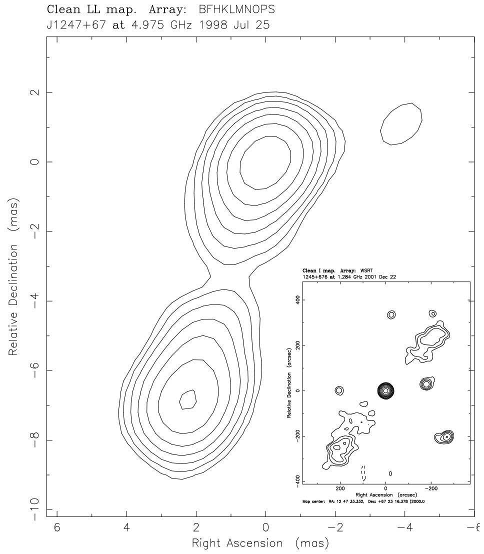

Fig. 5. 6cm VLBA image of the CSO-like core of the giant radio galaxy 1245+676. In the inset is the WSRT image of the whole radio galaxy, extending 1.9 Mpc.

4. Summary

There is clear evidence that Compact Symmetric Objects are young radio sources where the radio activity has started $10^2 - 10^3$ years ago. Kinematic ages have been estimated in about a dozen objects and more will be estimated in the next few years. Where other age estimate methods have been used, they are consistent with the kinematic ages. The number of detected velocities is not large enough for statistical trends to be noticed. As is seen in Figure 4 there are very few low luminosity CSOs with measured velocities. New samples of low z CSOs will remedy the situation.

The next question to be answered is whether the CSOs will evolve into the hundreds of kpc sized 'classical double' radio sources. Several evolutionary models have been considered, taking into account the relative number of CSOs, MSOs and 'classical doubles' in complete samples. Given luminosity (and possibly expansion velocity) evolution as the source propagates through a medium of decreasing density, it is found to first order that the relative numbers agree, for the medium and the larger sized objects with a small discrepancy in the smallest objects. It is also possible that some of the CSOs may not evolve into the 'classical doubles' but rather die young, and there seems to be increasing evidence that some CSOs are the visible phases of recurring radio activity (like 1245+676 and 0108+388).

References

Bicknell J. 2002, in Proc. 3rd GPS/CSS workshop, in press
Conway, J. E., et al. 1992, ApJ, 396, 62.
Conway, J. E., et al. 1994, ApJ, 425, 568.
Conway, J. E. 2002, NewAR, 46, 263
Lara, L., et al. 2001, A&A, 370, 409
Murgia, M., et al. 1999, A&A, 345, 769.
Murgia, M. 2002 in Proc. 3rd GPS/CSS workshop, in press
O'Dea, C. P., 1998, PASP, 110, 393.
Owsianik, I., & Conway, J. E. 1998, A&A, 337, 69 (OC98).
Owsianik, I., Conway, J., & Polatidis, A., 1998, A&A, 336, L37.
Owsianik, I., Polatidis, A. G., & Conway, J. E. 2002, A&A, submitted
Pearson, T. J., Readhead, A. C. S. 1988, ApJ, 328, 114.
Phillips, R. B., Mutel, R. L. 1982, A&A, 106, 21
Polatidis, A. G., et al. 1995, ApJS, 97, 1.
Polatidis A. G., et al. 1999, NAR, 43/8-10, 657
Readhead A. C. S., et al. 1994, in Proc. NRAO Workshop 23, 17
Readhead A. C. S., et al. 1996, ApJ, 460, 612. (RPX96)
Reynolds, C. S., Begelman M. C. 1997, ApJ, 487, L135.
Scheuer P. 1982, In IAU Symp. 97, 163
Stanghellini C., 2002, in Proc. 3rd GPS/CSS workshop, in press
Taylor, G. B., et al. 1996, ApJ, 463, 9 (TMP00)
Taylor, G. B., et al. 2000, ApJ, 541, 112
Tschager, W., et al. 2000, A&A, 360, 887.
Tzioumis, A. K., et al. 1989, AJ, 98, 36
Wilkinson, P. N., Polatidis, A. G., et al. 1994, ApJ, 432, L87.