The Jet Advance Speed in Compact Symmetric Objects

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Abstract. [Abstract]

1. Introduction

Since 1977 we have been engaged in a series of VLBI surveys of complete samples of powerful extragalactic radio sources (Pearson & Readhead 1988, hereafter PR; Polatidis et al. 1995; Thakkar et al. 1995; Xu et al. 1995; Taylor et al. 1994; Henstock et al. 1995). These have revealed that $\sim$10% of the objects in these samples are "Compact Symmetric Objects" (CSOs) in which high-luminosity radio emission regions are found on *both* sides of the center of activity on scales $<$ 1 kpc (Readhead et al. 1996a). The discovery of this class of object dates back to the work of Phillips & Mutel (1980, 1982), although there is still some uncertainty concerning the relationship between the Compact Doubles (CDs) discovered by Phillips & Mutel and the CSOs found in the PR survey. We have carried out multi-wavelength, multi-epoch observations of the 5 CSOs in the PR sample. In a companion paper, Taylor, Readhead, & Pearson (these proceedings) discuss the pinpointing of the center of activity in these five objects. In this paper we will discuss the jet advance speed in these small Cygnus A analogs.

2. The Detailed Morphology of CSOs and Relativistic Beaming

The five confirmed PR CSOs are shown in the figures of Taylor et al. (these proceedings). We see there that, in accordance with our definition for CSOs, there are extended, high-luminosity emission regions which straddle the center of activity. In addition, however, in all five PR CSOs there are bright regions — possibly jets — on one side of the center of activity, and any radio emission associated with the center of activity is weak. This last finding is in accordance with the findings of Phillips & Mutel for CDs — the centers of activity in CDs have proved to be extremely weak and difficult to observe. However, the bright one-sided features that we see in all five of the PR CSOs have not been seen in CDs. This raises some questions regarding the similarity between these different classes, but we believe that they do belong to the same class, although this remains to be fully demonstrated. For the present discussion we will concentrate on the PR CSOs. There are five confirmed CSOs, all galaxies, in the PR sample and one candidate CSO galaxy and one candidate CSO quasar. There are no other radio galaxies of extent < 1 kpc in the PR sample.

We estimate the ratio of the brightness of the jet to that of the counterjet, $R_{\rm j-cj}$, from the ratio of the highest surface brightness features at high frequencies in the two jets (excluding the terminal hot spots). We find that $R_{\rm j-cj} > 4$ for the PR CSOs. Wilkinson et al. (1994) have discussed the statistics of the PR sample and shown that the hot spots and lobes cannot be strongly beamed, however at the time of that paper we had not yet pinpointed the centers of activity with precision sufficient to show that all of these objects have fairly large $R_{\rm j-cj}$. It is interesting to consider whether the high values of $R_{\rm j-cj}$ are due to relativistic beaming. The numbers are small and if the value $R_{\rm j-cj} > 4$ observed in these objects is not due to beaming, and if this sample has no orientation bias, then we expect one quarter of the objects in the sample to have $R_{\rm j-cj} < 4$, and three-quarters of the objects in the sample to have $R_{\rm j-cj} > 4$, so that, in the present case we expect to see only two PR objects with $R_{\rm j-cj} < 4$. Thus we cannot rule out, on statistical grounds, the possiblity that the jets are beamed.

3. The Relationship Between Jet Advance Speeds and Hot Spot Pressure

The most direct way of measuring the jet advance speed, v_a, would be through proper motion measurements. Thus far, these have only placed upper limits on the separation speeds of the hot spots in CSOs (Conway et al. 1992, 1994; Taylor et al. 1996), with the most stringent limit ($v_a \leq 0.18\, h^{-1} c$) on 0108+388. Over the next decade it should be possible to improve these limits by an order of magnitude through high dynamic range VLBA mapping at high frequencies. In the absence of such a direct measure of the advance speed we have to resort to more model-dependent methods. In Table 1 are shown some relevant parameters of the jets and hot spots in the PR CSOs. These are small statistics, so we have to be cautious in interpreting the data. However, *if* these are not atypical and *if* the pressures in the hot spots are a good indication of the mean pressure over the life of the radio source in the CSO phase, there are some interesting implications of these results:

1. The higher pressure, and smaller, hot spot is on the jet side (3 out of 3 cases in which hot spots are clearly identifiable in both jets);

2. In 0108+388 the jet is only slightly longer than the counterjet, and in 0710+439 and 2352+495 the jets are, if anything, slightly shorter than the counterjets.

At first sight result the second point appears odd, because, if we assume that the hot spot pressure is balanced by ram pressure interaction with the external medium of density $\rho_{\rm ext}$, i.e.,

$$p_h = \rho_{\rm ext} v_a^2 \,, \tag{1}$$

then we might naively expect that the higher pressure jet would be moving faster. But, if the above results are not misleading they suggest that, to first order at least, the velocity of advance does not depend on the hot spot pressure, which suggests that

$$p_h \propto \rho_{\rm ext} \,. \tag{2}$$

Thus:

3. We believe that the external density is higher, by about a factor five, in each of these three objects on the jet side.

It may be, therefore, that the higher luminosity of the jet on this side is due to the higher density of the external medium.

If equation (2) does indeed hold in relativistic jets it suggests that they adjust the pressure and size of the hot spots is such a way that the velocity of advance is fairly independent of the external pressure.

Table 1. Ratios of Jet and Hot-Spot Parameters

Object	z	Jet Length (mas)	Counterjet Length (mas)	Jet-to-Counterjet Ratio: Length	Thrust	Hot-spot Pressure	Hot-spot Size
0108+388	0.699	4.4	3.4	1.3	1.4	4.8	0.56
0404+768	0.5985	67	85	0.8	...	...	...
0710+439	0.518	13.1	13.8	0.95	1.6	4.9	0.58
1358+624	0.431	40	31	1.3	...	...	...
2352+495	0.237	24	25.3	0.95	1.1	6.1	0.42
Mean				1.05 ± 0.1		5.3 ± 0.4	0.52 ± 0.05

4. The External Density in CSOs

We may place limits on the external density in CSOs through a variety of measurements of different types of absorption in the emission from the nuclear regions (Readhead et al. 1996a). The limits we derive on the density and temperature of the external medium in 2352+495 are shown in Figure 1. A strong limit on the H II density may be determined from the optical depth due to free-free absorption at 151 MHz and absence of X-ray emission (O'Dea et al. 1996). We see that the H II number density must be $< 10^3$ cm^{-3}. We have searched for H I and CO ($J = 0 \rightarrow 1$) absorption in this objects and find upper limits on the optical depth of 5% and 10%. Due to the radiative excitation of the atoms and molecules by the photon flux from the hot spots, these limits on τ do not provide such stringent limits on the number density as might be expected (Readhead et al. 1996a). The derived upper limits are ~ 800 cm^{-3} in H I and 10^5 cm^{-3} in H_2. The possibility of a dense molecular external medium cannot, therefore be ruled out by these absorption observations.

An independent estimate of the external density can be made based on a comparison of the Balmer decrement in the narrow lines and the extinction in the underlying galaxy continuum. This yields a density of ~ 3 cm^{-3}, assuming the narrow line region is a few hundred parsecs across, and assuming conditions in this galaxy that are similar to our own and a λ^{-1} extinction law. However, if

Figure 1. Temperature–number density plot for the external medium in 2352+495, assuming a confining cloud of radius 200 pc. The velocity of advance, derived from the mean hot-spot pressure, is shown on the top axis. The upper limit to the optical depth at 151 MHz provides a lower limit to the temperature for an ionized cloud. The upper limit to the X-ray luminosity excludes the portion of the T, n_p plane to the right of the X-ray curve provided there is no significant absorption of X-rays within the host galaxy. Also shown are *hard* and *soft* limits provided by the H I absorption observations and a hard limit provided by the CO absorption measurements. The region occupied by the narraow-line clouds is shown by the two starred points, which correspond to temperatures of 10 000 and 20 000 K. The region occupied by the "hot intercloud medium" is also indicated. The locus for an external medium in pressure equilibrium with the narrow-line clouds is shown by the line marked "pressure balance with NLC". The region indicated by horizontal dashes is excluded for any type of medium, and the region shown by horizontal dotted lines is excluded for all except an H_2 medium.

the emission and absorption regions are intermixed, the Balmer decrement could lead to a significant underestimate of the dust in this region.

An alternative estimate of the external density can be derived from equation (2) under the assumption that the same relationship holds for large Fanaroff–Riley type II (FR II) objects. The typical hot spot pressure in these objects is $\sim 10^4$ times smaller than that in the CSOs (Readhead 1995; Readhead et al. 1996a,b). If we assume a typical external density for large FR II objects of $\rho_{\rm ext} \sim 10^{-3}$ cm^{-3}, then the implied external density in CSOs is ~ 10 cm^{-3}. A density of a few cm^{-3} would also be consistent with the external medium being the hot intercloud medium in pressure equilibrium with the narrow line clouds (see Figure 1).

5. The Jet Advance Speed

The jet advance speed in 2352+495, based on the hot spot pressure, is shown on the upper axis of Figure 1. The hot-spot pressure implies an external density of $10(v_a/0.02c)^{-2}\,{\rm cm}^{-3}$, an age for 2352+495 of $\sim 10^4(v_a/0.02c)^{-1}$ yr, and a mass within a 200 pc radius of $\sim 10^7(v_a/0.02c)^{-2}\,M_\odot$. In the case of 0108+388, the densities and masses are a factor of eight higher. The most stringent limit on the advance speed comes from 0108+388, in which an upper limit of $10^{10}\,M_\odot$ within a radius of 200 pc, which is the maximum mass seen in the inner few hundred parsecs of even the most ultraluminous starburst galaxies, implies $v_a > 2\times10^{-3}\,c$ and an age at 50 pc of $< 8 \times 10^4$ yr.

6. Discussion

A regular pattern seems to be emerging in the CSOs:

1. The all have very weak radio cores;
2. The ratio of jet length to counterjet length is close to unity;
3. They all have features which can be interpreted as bright jets and weak counterjets;
4. Higher pressure hot spots are seen on the jet side;
5. Smaller hot spots are seen on the jet side.

The numbers of CSOs are still small, so we must be cautious in interpreting these results, but, if the early results on CSOs are not misleading and if the differences in the hot spots are stable features in these objects, the fact that the smaller, higher pressure hot spots occur on the jet side argues against beaming as an explanation for the observed asymmetries. It might be possible to reproduce this effect by a combination of beaming in the jets and in the hot spots themselves, but the results raise the interesting possibility that the relative jet-counterjet brightness ratios are due not to relativistic beaming, but to different external densities on the two sides of the center of activity. If the observed differences are indeed due to differences in the external medium, and not just to orientation, this could have important consequences for the interpretation of large-scale and small-scale jet asymmetries seen in powerful FR II radio galaxies and quasars.

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