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The origin of wide-angle tailed radio galaxies

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ABSTRACT

To investigate the origins of wide-angle tailed radio sources (WATs), we have compiled a sample of these systems in Abell clusters for which X-ray data exist. Contrary to conventional wisdom, the WATs are found to be significantly displaced from the X-ray centroids of their host clusters. The bends in the WATs' radio jets are found to be oriented preferentially such that they point directly away from or toward the cluster centre, with more of the former than the latter. If this morphology is attributed to ram pressure, then the WATs are on primarily radial orbits, with more approaching the X-ray centroid than receding. There is also some evidence that the in-coming WATs are on average further from the X-ray centroid than the out-going ones. All of these observations strongly support a scenario in which WATs are created in cluster mergers.

Key words: surveys – galaxies: clusters: general – galaxies: jets – galaxies: kinematics and dynamics – X-rays:galaxies

1 INTRODUCTION

Wide angle tail radio galaxies (WATs) form a class of radio galaxies, usually found in clusters, whose radio-emitting jets have been bent into a wide 'C' shape. This structure gives the immediate impression that the jets are being swept back by the dynamic pressure resulting from the motion of the associated galaxy through the surrounding intracluster medium (ICM). This 'ram pressure' model was first developed by Begelman, Rees & Blandford (1979), and studied in more detail by Vallée, Bridle & Wilson (1981) and Baan & McKee (1985).

Unfortunately, there is a piece of evidence that seems to contradict this intuitively-appealing model. WATs are usually associated with the brightest clusters ellipticals (D or cD galaxies), and these galaxies are generally found at rest, close to the centres of clusters (Quintana & Lawrie 1982, Bird 1994, Pinkney 1995). From a theoretical point of view, this finding can be understood since models of cluster formation imply that large galaxies form close to their cluster centres (Bode et al. 1994; Garijo, Athanassoula & García-Gómez 1997). Even if a massive galaxy were initially placed on a high-velocity orbit that carried it far out in its cluster, dynamical friction would rapidly drag it down to rest at the centre of the system (Ostriker & Tremaine 1975).

Since it seems that the D/cD galaxies that host WATs should lie at rest in the centres of their clusters, they should not possess the motion required to produce the observed bends in their radio jets by ram pressure. It has therefore been thought necessary to invoke alternative mechanisms to explain the observed bends in WATs' jets. One candidate for this mechanism is an electromagnetic force arising from the interaction between a jet that carries a net electrical current and the magnetic field in the ICM (Eilek et al. 1984). Given our poor understanding of currents in jets and magnetic fields in clusters, this model has not been extensively explored. One problem with it is that it requires a highly and favourably ordered magnetic field in order to produce the symmetric shape of WATs. Alternatively, jets could be deflected by collisions with dense clouds in the ICM. Although this process may be at work in some radio galaxies whose jets are deflected and disrupt abruptly (Burns et al. 1986), again it has difficulty reproducing the large-scale symmetric structure of WATs. Thus, neither of the suggested alternative jet-bending mechanisms are entirely satisfactory.

A possible solution to this dilemma has come from the realization that clusters are dynamically young, and merge frequently. Theoretical and observational studies have forced us to discard the idealized picture of a spherical relaxed cluster that is isolated and does not interact with its surroundings. Instead, structure in the Universe is now viewed as evolving hierarchically, with large feature such as clusters forming through the repeated mergers of smaller groups (e.g. Evrard 1990; Jing et al. 1995; Frenk et al. 1996).

It has therefore been suggested that the galaxy motions required to bend WATs by ram pressure are a by-product of collisions between clusters (Pinkney, Burns & Hill 1994; Gómez et al. 1997a, b; Loken et al. 1995). Consider a radio galaxy located at the centre of a cluster. If this cluster collides with a second comparable system, then the collisional nature of the ICM means that the kinetic energy of the gas will rapidly dissipate, and the two separate gaseous components will merge into a single structure. The radio galaxy, on the other hand, is an essentially collisionless system that will not be decelerated at the same rate as the surrounding ICM, and so it will be kicked into motion as efficiently as a passenger in a car accident who is not wearing a seat belt. The motion of the galaxy relative to the ICM will then generate the ram pressure needed to bend the radio jets. Some recent support for this idea has come from the work of Novikov et al. (1999), who found that the jets of WAT radio galaxies tend to be aligned with the long axis of any surrounding supercluster; it is along this axis that one would expect cluster mergers to occur preferentially (Colberg et al. 1999).

In this paper, we make direct observational tests of the merger theory by investigating the properties of a sample of WAT sources. The simplest prediction of this scenario is that, unlike most D/cD galaxies, the hosts of WATs will not generally lie at the centre of their clusters. This prediction can most readily be tested by comparing the location of the WAT to that of the centroid of the cluster's X-ray emission, which should lie close to the global minimum of the cluster's potential. In a major merger, the X-ray emission is likely to be significantly disturbed, with shock heating at the collision interface, and large-scale flows set up in the combined ICM, so some care must be taken in equating the X-ray centroid with the mass centre of the cluster. However, the global distribution of X-ray emitting gas will still reflect the morphology of the merging system, so a centroid measured in a manner that is not heavily weighted toward localized features should still provide a reasonable estimate of the cluster centre.

Once the centroid has been determined, we can also determine the direction in which the radio jets are bent relative to the cluster centre. If ram pressure is responsible for this morphology, then we can use this information to study the orbits followed by the WATs, to see if they are consistent with the cluster merger model.

The remainder of this paper, describing these tests, is laid out as follows. Section 2 presents the process by which radio galaxies were selected to represent the WAT class. Section 3 describes the X-ray observations of the clusters containing these systems, and Section 4 presents the analysis that we have applied to them in order to measure the centroids and spatial extents of their ICMs. In Section 5, we discuss the spatial distribution of the WATs relative to their host clusters as inferred from the X-ray data, and we quantify the orbits that the WATs follow as derived from the directions in which the radio jets are bent. Section 6 summarizes the findings, and discusses their implications for the merger theory.

2 SAMPLE SELECTION

Over the last ten years, Abell clusters of galaxies have been extensively mapped at the radio frequency of 1.4 GHz by Zhao, Burns & Owen (1989), Owen, White & Burns (1992), and Owen, White & Ge (1993). Maps of the radio sources found in these clusters, along with the optical identifications of the galaxies that host them, are given by the previous works and by Ledlow & Owen (1995a) and Owen & Ledlow (1997). This sample of radio galaxies in Abell clusters is complete for sources with a redshift of $z < 0.09$ and flux density at 1.4 GHz of $S_{1400} > 10\,\mathrm{mJy}$. Additionally, the sample has been extended to include clusters out to a redshift of $z = 0.25$. This radio survey forms the basis of the present investigation.

As the primary criterion, we have selected sources on the basis of their morphology. Extended sources that show clearly the characteristic 'C' shape of WAT sources have been collected to define a sample of WATs in Abell clusters. Some radio galaxies which have been previously classified as WATs by various investigators, but whose jets do not appear to be significantly bent, are not included in the present sample. An example of such a source is the radio galaxy 0043+201 in Abell 98; although, for the study of its dynamics it has been treated as a bent WAT source (Krempec-Krygier & Krygier 1995), radio maps do not show the characteristic bent structure (O'Donoghue, Owen & Eilek 1990).

Radio galaxies whose jets were found to be smaller than $100h_{50}^{-1}$ kpc have also been excluded. In many cases, the optical light distribution of these galaxies has been found to extend out to such radii (e.g. Owen & White 1991, Graham et al. 1996). Since we are primarily concerned with quantifying the interactions between radio jets and the ICM, it is important to exclude small sources, whose jet dynamics are likely to be significantly affected by the galaxy's own interstellar medium. The WAT sources PKS 2322−123 in Abell 2597, 2207−124 in Abell 2420, 1519+488B in Abell 2064, 1508+059 in Abell 2029, NGC 4874 in Coma, 1142+157 in Abell 1371, 0720+670 in Abell 578 were all excluded on this basis.

The final sample of WATs in Abell clusters is presented in Table 1. The first column lists the names of the radio source, while the next two [(2) and (3)] give the position of the host galaxy. In column (4) the Abell cluster that hosts the WAT is listed, and column (5) gives its redshift. Additionally, this table gives details of the available X-ray observations of the field containing the WAT (see §3).

The selection of a radio source and its morphological classification as a WAT are dependent on the quality and resolution of the available radio data. If the resolution of the radio observation is not high enough to reveal the detailed structure of a WAT, it might be mistaken for a different class of radio galaxy (such as a narrow-angle tailed radio galaxy) and not included in the sample. We have therefore examined the literature to see if higher quality radio maps exist for any of the WAT candidates. Only a few sources were found to have been observed at higher resolution, most of which are presented by O'Donoghue et al. (1990). However, since we have restricted the sample to contain sources that are larger than $100h_{50}^{-1}$ kpc and that lie at a redshift of $z < 0.25$, there should be very few WATs that have not been observed with the requisite angular resolution – at a redshift of 0.25, a WAT that meets our criteria will have an extent of ~ 30 arcseconds, significantly greater than the spatial resolution of almost all the radio data.

Confirmation that Table 1 contains a representative

Table 1. WATs in Abell clusters

(1) Source name	(2) Optical Position(1950) R.A. h m s	(3) Optical Position(1950) DEC ° ′ ″	(4) Abell cluster	(5) z	(6) *ROSAT* OBS. Sequence number	(7) *ROSAT* OBS. Exposure (sec)
0035+180	00 35 17.19	+18 04 23.9	A69	0.1448	–	
0110+152	01 10 20.45	+15 13 35.2	A160	0.0444	rh800953	16501
0123–016B, 3C 40	01 23 27.55	–01 36 18.9	A194	0.0180	rp800316	24482
0141+061	01 41 19.20	+06 09 34.0	A245	0.0788	–	
0146+138	01 46 30.66	+13 48 08.2	A257	0.0706	–	
0255+058A, 3C 75	02 55 02.99	+05 49 37.0	A400	0.0238	rp800226	23615
0255+058B	02 55 03.08	+05 49 20.9				
0327+246B	03 27 32.25	+24 37 36.0	A439	0.1063	–	
0647+693, 4C 69.08	06 47 54.58	+69 23 31.5	A562	0.1100	rp800500	5865
0658+330	06 58 52.48	+33 01 47.2	A567	0.1270	–	
0705+486	07 05 21.39	+48 41 47.2	A569	0.0195	wp800575	4181
0803–008, 3C 193	08 03 05.14	–00 49 43.1	A623	0.0871	rp800506	4447
0836+290	08 36 13.50	+29 01 12.9	A690	0.0788	–	
0838+32, 4C 32.26	08 38 06.74	+32 35 42.2	A695	0.0694	–	
0908–103	09 08 32.61	–10 21 33.7	A761	0.0921	–	
0909+162	09 09 48.50	+16 12 23.0	A763	0.0851	–	
1011+500	10 11 26.68	+50 00 27.6	A950	0.2081	rp700220	5151
1025+040	10 25 47.94	+04 00 52.1	A1024	0.0733	–	
1108+410A	11 08 54.20	+41 03 25.7	A1190	0.0794	–	
1131+493, IC 708	11 31 16.25	+49 20 19.8	A1314	0.0338	wp800392	2940
1159+583, 4C 58.23	11 59 30.41	+58 18 51.3	A1446	0.1035	rp800501	7094
1200+519	12 00 34.13	+51 57 12.4	A1452	0.0630	–	
1221+615	12 21 07.38	+61 31 29.6	A1529	0.2324	–	
1225+636	12 25 33.20	+63 39 37.8	A1544	0.1459	–	
1227+119	12 27 20.34	+11 57 13.1	A1552	0.0843	wp800577	3398
1231+674, 4C 67.21	12 31 03.88	+67 24 17.2	A1559	0.1071	–	
1233+168, 4C 16.33	12 33 55.19	+16 48 47.6	A1569	0.0784	rp800504	3687
1243+26(7)	12 43 54.69	+26 43 39.3	A1609	0.0891	–	
1300+32(1)	13 00 54.54	+32 06 08.1	A1667	0.1648	–	
1306+107A, 4C 10.35	13 06 34.40	+10 45 32.8	A1684	0.0864	–	
1320+584	13 20 58.62	+58 25 41.3	A1731	0.1932	–	
1333+412, 4C 41.26	13 33 09.52	+41 15 24.1	A1763	0.2074	rp800252	15659
1415+084	14 15 02.92	+08 26 19.8	A1890	0.0570	rh800649	13836
1433+553	14 33 54.92	+55 20 53.2	A1940	0.1396	rp800502	3433
1445+149	14 45 40.62	+14 59 19.5	A1971	0.2084	–	
1636+379	16 36 15.71	+37 58 53.7	A2214	0.1610	rp800503	5209
1638+538, 4C 53.37	16 38 24.50	+53 52 30.8	A2220	0.1106	rp201446	24402
1820+689	18 20 01.32	+68 55 24.0	A2304	0.0880	rp800498	5412
1826+747	18 26 23.40	+74 42 05.8	A2306	0.1271	rp800505	4470
2236-176	22 36 30.07	–17 36 04.8	A2462	0.0698	rp800495	4289
2330+091	23 30 58.81	+09 08 58.7	A2617	0.1623	–	
2335+267, 3C 465	23 35 58.93	+26 45 16.2	A2634	0.0321	rp800014	20400
2336+212	23 36 11.04	+21 13 26.3	A2637	0.0707	rp000111	2580

sample of WATs comes from comparing the optical magnitudes of the galaxies that host them with their total radio power. Figure 1 shows the radio luminosity at 1.4 GHz versus the absolute magnitude of the galaxies that host the WATs. The absolute magnitude is taken from Ledlow & Owen (1995b), and Owen & White (1991), and the radio luminosities are calculated from the fluxes given by Ledlow & Owen (1995a) using their adopted cosmology. The plot is directly comparable to the one that was presented by Ledlow & Owen (1996), which was constructed using all the radio galaxies in their sample and others collected from the literature. The solid line represents the division between galaxies of Fanaroff-Riley class FR I and FR II (Fanaroff & Riley 1974). Canonically, WATs are found to be FR I sources in bright ($-22 > M_{24.5} > -24.5$) galaxies (O'Donoghue, Eilek & Owen 1993), and it is clear that the current sample of sources meets these requirements.

3 X-RAY OBSERVATIONS

We have searched the *ROSAT* data archive in order to find which of the clusters containing WAT sources have been

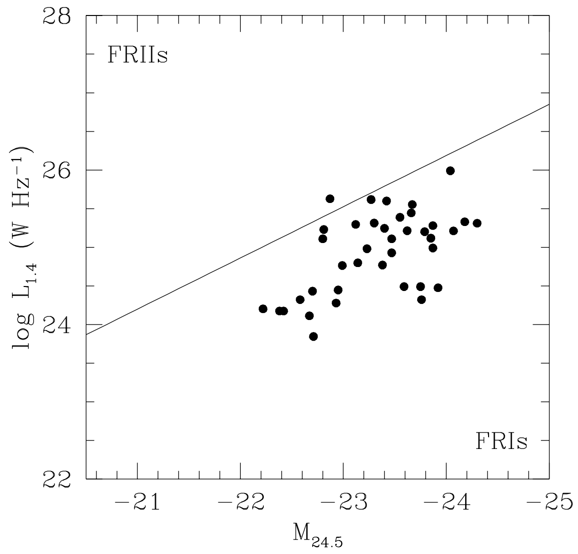

Figure 1. The radio luminosity – optical magnitude diagram for the candidate WAT sources. The solid line divides the plane between FR I and FR II radio sources. This plot is directly comparable to the one presented by Ledlow & Owen (1996).

observed in the X-ray energy band. The search was constrained to a circle of 30 arcmin around each radio source. The *ROSAT* observations found and used in the subsequent analysis are presented in Table 1 [column (6)]. The sequence numbers designate the detector used for each particular observation ('wp' or 'rp' for PSPC, and 'wh' or 'rh' for HRI). All these datasets, apart from the HRI observation of Abell 160, are publicly available. Some of the clusters with PSPC observations have also been observed by the HRI detector, but these generally-inferior datasets are not reported, or used here. The total exposure times of the observations are also given in column (7) of Table 1. Notes on the individual sources with X-ray observations are given in the Appendix.

The clusters were also observed in the *ROSAT* All Sky Survey (RASS) performed with the PSPC. However, as will become clear from the discussion below, the short exposures in the survey observations mean that these data are not suitable for the present investigation,

It is clear from Table 1 that less than half of the clusters in the sample of Abell clusters that contain WATs have been observed with *ROSAT*. In order to increase the coverage of X-ray observations over the sample, the *Einstein* database was also searched. Only three of the clusters that have not been observed by *ROSAT* have *Einstein* observations (A439, A690, A1609). Unfortunately, in all these cases the exposure times were too short to reveal any sign of the emission from the ICM of the associated cluster. Therefore, only the *ROSAT* observations could be used in this analysis.

The sparsity of the X-ray observations reduces the sample of WATs in Abell clusters. It also raises the possibility that the clusters for which X-ray data exist may form a biased subsample of the WAT systems. In order to check this possibility, we have compared the redshift distributions, cluster richness distributions, and radio power distributions of the available subsample and the complete sample. In each case, a Kolmogorov-Smirnov test (K-S test; Press et al. 1986) fails to show any evidence that the subsample is in any way biassed.

4 DATA ANALYSIS

4.1 X-ray centres

In order to quantify how far a WAT is offset from its host cluster's centre, we need an objective definition of the centroid of the X-ray emission. As mentioned in the Introduction, in a merger one would expect the details of the X-ray emission to be rather complicated, so we need a measure of the cluster centroid that is insensitive to this complexity. We discuss the possible impact of such complexity on the analysis later in this section. Given the short exposures in some of the X-ray observations, we also need to be sure that the method used for calculating the cluster centre provides a robust estimate, even when the quality of the data is rather low. Finally, it is important that we adopt an objective process: if we were to examine the radio maps before estimating the X-ray centroid, there would be a danger that we might bias our results by, for example, picking out the X-ray peak that happens to lie closest to the WAT. Such a reinforcement of any pre-existing prejudice must be avoided, so, as far as possible, we have carried out the X-ray centroid calculations without prior reference to the WAT location, and using an algorithm that requires as little human intervention as possible. In this section, we discuss the adopted procedure, and the resulting determinations of the cluster center location.

Having first removed any bright point sources from the X-ray data by interpolation, the task we are faced with is quantifying the distribution of diffuse gas so as to define its centroid. After some experimentation, it became apparent that the most robust way of making such a quantification was also pretty much the simplest. The emission from the central region of the cluster was projected on to the x- and y-axes of the image, and the counts on each projected axis were fitted by a Gaussian function. In each fit, the amplitude, width, and centre of the Gaussian were left as free parameters. The best fit model provides, along with the best-fit values of the other free parameters, the centre of the Gaussians in each axis; these numbers provide a surprisingly robust measure for the location of the centre of each cluster.

The cluster X-ray centres calculated in this way are presented in Table 2 [columns (2), (3)]. This procedure also provides the errors of the determined cluster centre, which are given in Table 2 [column (4)]. The results and their position on the X-ray images were also examined by eye, to make sure that the adopted centre had not been unduly influenced by any residuals from the subtraction of the point sources. It is important to stress that we make no claim that these simple Gaussian fits describe the actual distribution of X-ray emitting gas; rather, the fitted parameters simply provide a robust and objective estimator for the location of the X-ray centroid. We visually inspected each derived centroid to check that the process really does provide a credible measure of the centroid; in almost all cases, the derived location was found to agree well with a "χ-by-eye" fit, but without the danger of statistical biasses inherent in the latter subjective process.

Table 2. X-ray results

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Cluster centre (1950)		Positional				
Cluster	RA h m s	Dec ° ′ ″	error (arcsec/kpc)	d (arcmin/h_{50}^{-1}kpc)	r_c (h_{50}^{-1}kpc)	θ (degrees)	$\sigma_{\|\theta\|}$ (degrees)
A160	01 10 20.2	+15 15 04.6	25/32	1.49/115.3	–	–111.1	15.5
A194	01 23 10.5	–01 36 34.6	30/16	4.27/133.2	296±39	2.3	6.8
A400	02 54 57.7	+05 47 40.1	30/21	2.25/93.1	236±5	–0.2	12.7
A562	06 47 57.9	+69 24 08.1	5/16	0.68/130.6	144±13^g	39.1	7.0
A569	–	–	–	–	–		
A623	08 03 05.1	–00 48 50.0	30/76	0.88/133.6	162±57^g	96.7	29.6
A1314	11 32 04.5	+49 23 03.4	20/20	8.33/489.8	322±40	35	2.3
A1446	11 59 27.3	+58 19 25.2	5/15	0.70/126.4	350±17^g	–13.5	6.8
A1552	12 27 39.5	+12 01 12.0	–	6.16/905.5	–	–14.5	–
A1569	12 33 50.5	+16 49 31.7	40/20	1.34/183.3	268±162^g	–3.3	6.2
A1763	13 33 06.5	+41 15 09.3	–	0.62/246.6	428±10	176.1	–
A1890	14 15 05.4	+08 26 39.8	50/83	0.70/69.7	301±130	110.8	50.0
A1940	14 33 43.4	+55 21 00.9	15/61	1.64/399.5	304±145^g	143.5	8.7
A2214	16 36 13.3	+37 58 54.3	–	0.48/134.8	263±32^g	36.1	–
	16 35 47.2	+37 59 13.9	–	5.63/1580.9		33.9	–
A2220	16 38 44.6	+53 52 54.7	–	2.99/577.7	328±43	–4.2	–
A2304	18 20 43.4	+68 56 03.5	–	3.84/589.8	289±32^g	20.2	–
A2306	18 26 26.8	+74 42 48.1	20/74	0.74/164.3	133±16^g	–8.0	24.2
A2462	22 36 29.7	–17 36 11.9	10/20	0.15/18.3	332±22^g	143.6	47.5
A2634	23 35 53.6	+26 43 56.8	15/14	1.78/99.3	310±16	155.7	8.0
A2637	–	–	–	–	–		

NOTE: ^{g} core radii calculated by Gómez et al. (1997b)

In a few cases, as described in more detail in the Appendix, such a procedure proved unfeasible, mainly because the cluster is clearly bimodal, so the whole concept of 'a cluster centre' is flawed, and a single Gaussian cannot be fitted unambiguously to the data. In such cases, the brightest peak of the X-ray emission was taken to indicate the centre of the cluster.

The centres of some of the clusters that host WATs have previously been determined by Briel & Henry (1993), Pierre et al. (1994), and Ebeling et al. (1996) using the RASS. Comparison of their results to the positions reported in Table 2 supports the concern mentioned in §3 that the short exposures in the RASS could lead to inaccurate determinations of the cluster centres. In several cases the centres that are given by these investigations coincide with the optical galaxy that hosts the radio source. Since radio galaxies are often also strong X-ray emitters, it is very likely that in these cases the analysis based on RASS data picked up the location of the emission coming from the WAT rather than the centre of the ICM distribution.

The X-ray light distributions of the clusters that host WATs generally appear somewhat irregular, and elongated (a point noted by Gómez et al. 1997b). These observations are clearly not consistent with the simple picture of the ICM forming a spherically-symmetric structure, and some care must be taken in interpreting the data. However, the procedure adopted here for determining the centre of the X-ray distribution provides a robust estimator for the centroid of the emission even for elongated and irregular clusters, since it does not attempt to follow any small scale irregularities in the data.

One interpretation of the irregularities in the X-ray emission is that it may well reflect the recent merger between clusters that might also be responsible for producing the WAT. This interpretation raises a further concern: the violent hydrodynamical processes that occur in the merger between two clusters' ICMs mean that the centroid of the X-ray emission need not coincide with the merger remnant's centre of mass, so that it may not provide a good fiducial measure of the cluster centre. Hydrodynamic simulations of merging clusters of galaxies (Roettiger, Stone & Mushotzky 1997, and references there-in) confirm that such shifts do occur. However, even for the most extreme case of a collision between two equal-mass clusters, the shift is much less than the cluster core radius. As we shall see below, such shifts are small compared to most other distances in this analysis, so the X-ray centroid definitely provides an adequate measure of a cluster's centre for the current study.

4.2 Size of the cluster

The WAT radio sources presented here are located in a variety of environments, from poor (richness class $R = 0$) clusters up to relatively rich ($R = 3$) systems. The extent of the clusters might be expected to vary accordingly. Therefore, if we are to compare results for different WATs, it may be useful to scale distances by the sizes of their host clusters. In this study, where we are interested in the impact of the

ICM on the jets, a sensible scale-length is provided by the core radius of the distribution of the ICM.

Core radii of some of the clusters that host the WATs have been previously measured by Gómez et al. (1997b), using the *ROSAT* PSPC observations. They fitted the surface brightness distribution of each cluster by the traditional β-model, leaving the central surface brightness, the core radius, and the β parameter to be determined by the fit. Their calculated values for the core radii, converted from their choice of cosmology to the one adopted here, are given in Table 2.

For the remainder of the clusters, whose X-ray observations have not been previously analysed, we have carried out a similar procedure. Counts were integrated in concentric annuli, centered on the cluster centre as found in §4.1. The width of each annulus was different for each cluster, depending on the number of photons detected. All the point sources lying on the image of the clusters were masked out. The radial profile was then fitted by the β-model, with the background left as free parameter to be determined by the fit. The limited integration time for most of these observations prevented us from satisfactorily fitting for both β and r_c, so we fixed $\beta = 0.65$, which is an average value for this parameter found from the study of other similar clusters (Jones & Forman 1984). The resulting values of the core radii are given in column (6) of Table 2.

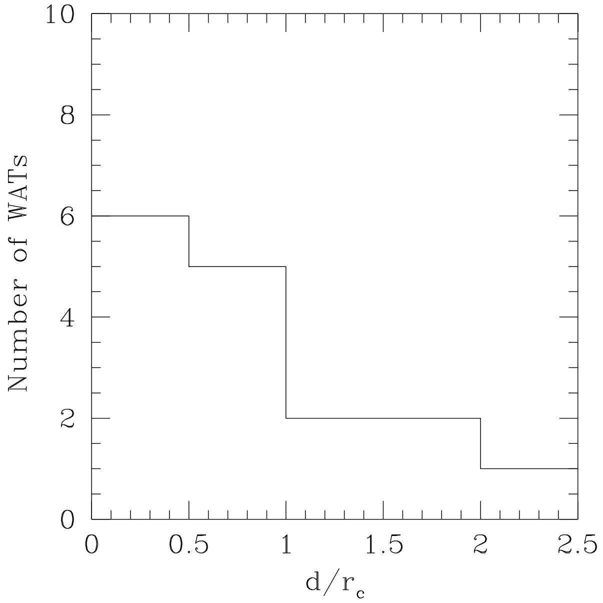

Figure 2. The distribution of distances of WAT sources from their cluster centres, measured in units of the clusters' core radii.

5 RESULTS

5.1 The spatial distribution of WATs in clusters

Having measured the X-ray location of a cluster's centre, we can now quantify the offset between the location of a WAT and its cluster X-ray centroid. The distribution of observed distances scaled with the core radius of each cluster is presented in Fig. 2. It is apparent that, although WATs are found preferentially toward the centres of clusters, they are spread over a wide range of distances from the cluster centre. In fact, this figure does not include the most extreme case of Abell 2214, where the WAT lies at ~ 6 core radii. It should also be borne in mind that these offsets are even more significant once projection effects are taken into account, since the observed projected radius of a WAT only places a lower limit on its true distance from the cluster centre. Thus, we have found strong confirmation that WATs are not all located close to the centres of their host clusters.

5.2 Orientation of WATs

Since we have shown that the galaxies which host WATs often lie far from the X-ray centroids of the surrounding clusters, it is at least plausible that the radio jets in WATs are bent by ram pressure as their host galaxies move relative to the ICM. In this section, we attempt to further investigate this scenario by using the direction in which the jets are bent to determine the WAT galaxies' orbits. This approach has previously been taken – and its limitations discussed – by O'Dea et al. (1987); they explored the dynamics of clusters using the morphology of the more dramatically-bent radio galaxies known as narrow-angle tailed sources.

The parameter of interest for such an investigation is the angle between the line connecting the cluster centre to the radio galaxy, and the line that bisects the angle between the two radio lobes. We define this angle, θ, to be measured counterclockwise from the radius vector that connects the cluster centre to the optical galaxy. If the radio jets are bent by ram pressure, then such a definition assigns $\theta = 0$ for a galaxy travelling directly toward the cluster centre on the plane of the sky, and $\theta = 180$ deg for one travelling radially away from the cluster centre. The values for θ obtained from the measured X-ray cluster centroids, the locations of the WATs, and their observed radio morphologies are presented in Table 2.

For each system, the error in θ mainly depends on the accuracy of the position of the cluster centre; the position of the optical galaxy has been measured with an accuracy of 1 arcsec (Ledlow & Owen 1995b). For the sources for which a measurement of the error for the position of the cluster centre exists, the error in θ is calculated and presented in Table 2. Generally, the largest inaccuracies of θ correspond to sources which lie very close to the cluster centre, since a small change in the position of such a source corresponds to a large change in angle.

Figure 3 shows the distribution of θ for the WAT sources in this sample. Since the geometry is symmetric about $\theta = 0$, we have plotted $|\theta|$, with the angle defined in the range $-180 < \theta < 180$ degrees.

It is apparent from Figure 3 that there seems to be a concentration of WAT sources with $\theta \sim 0$ degrees. We therefore now investigate whether this concentration might arise from a statistical fluctuation in the small number of observations, and, if not, what distribution of orbits might give rise to such a distribution.

If the orbits of WATs were entirely random and isotropic, one would expect to observe all angles θ with equal probability. When the distribution of $|\theta|$ in Figure 3 is com-

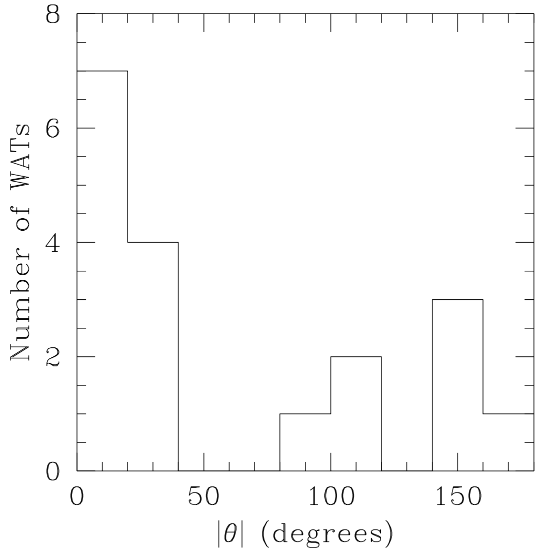

Figure 3. The distribution of the observed angles for all the 18 WATs.

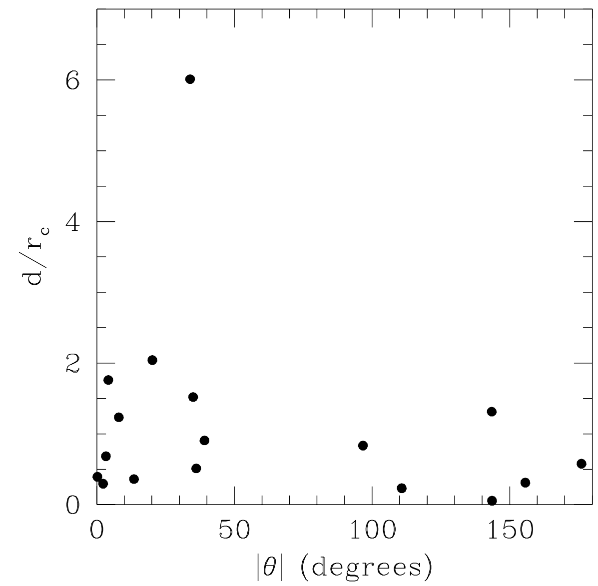

Figure 4. The distance of each WAT source from the cluster centre versus the angle of its motion as indicated by its jets. The WATs in Abell 160 and Abell 1552 are not included because the existing X-ray data do not allow a reliable determination of r_c for these systems.

pared with such a uniform distribution using the K-S test, the hypothesis that they have the same distribution can be rejected at the 99.9% confidence level. Thus, the spike at $|\theta| \sim 0$ is statistically significant, and allows us to confidently rule out the possibility that WATs follow purely random orbits.

We can exclude the possibility of circular orbits with even greater confidence. The distribution of θ that one would expect for circular orbits is somewhat more complicated due to projection effects. O'Dea et al. (1987) have quantified this distribution, and they found that the expected number of galaxies has a minimum at $|\theta| = 0$ degrees, and rises to a sharp maximum at $|\theta| = 90$ degrees, before dropping back to a minimum at $|\theta| = 180$ degrees. Not surprisingly, this distribution is inconsistent with the distribution in Figure 3 which peaks at $|\theta| = 0$ and 180 degrees; a K-S rejects the possibility that the orbits of WATs are circular at the 99.99% confidence level.

We can therefore conclude that the orbits of WATs are predominantly radial. If the orbits were purely radial, then the distribution of θ should consist of delta-function spikes at $|\theta| = 0$ and 180 degrees. Since there are observational uncertainties in the values of θ, we would expect the distribution to be somewhat broadened. The presence of a few WATs with intermediate values of θ suggests that the orbits cannot be completely radial. However, it is notable from Figure 4, which plots the distance of the WAT from the cluster X-ray centre as a function of $|\theta|$, that the WATs at intermediate angles tend to lie at small cluster radii, where the uncertainties in the values of θ are greatest.

5.3 In-coming versus out-going galaxies

A tail angle of $0 < |\theta| < 45$ degrees indicates that the WAT is moving towards the centre of the cluster (in-coming), while an angle of $135 < |\theta| < 180$ degrees implies an out-going WAT. Figure 3 gives the distinct impression that there are more WATs travelling toward the centres of clusters than there are outward-bound systems. In fact, there are $n_{\rm in} = 11$ in-coming WATs and only $n_{\rm out} = 4$ out-going systems, and a binomial distribution with $p = 0.5$ will produce such an imbalance only $\sim 6\%$ of the time. Thus, we can conclude that the difference between the observed number of in-coming and out-going WATs is significant at a level of more than 90%.

A further impression one gains from Figure 4 is that out-going WATs are found closer to the cluster centre than the in-coming ones. Figures 5 (a) and (b) show the radial distribution of in-coming and out-going WATs respectively. The 10 in-coming WATs with measured values of r_c lie at a mean radius of $(1.5 \pm 0.5)r_c$, while the 4 out-going have a corresponding mean radius of $(0.6 \pm 0.3)r_c$. Applying Student's t-test to these data, we find that the two means are significantly different at the 95% confidence level. However, it should be pointed out that this result is not very robust: if we exclude the single in-coming WAT with $d = 6r_c$ (in Abell 2214), then the difference ceases to be statistically significant.

6 SUMMARY AND DISCUSSION

We have defined a sample of WAT radio sources in Abell clusters in order to investigate the hypothesis that these sources are bent by ram pressure induced when their host galaxies are kicked into motion by a cluster merger. Archival *ROSAT* observations have been used to define more accu-

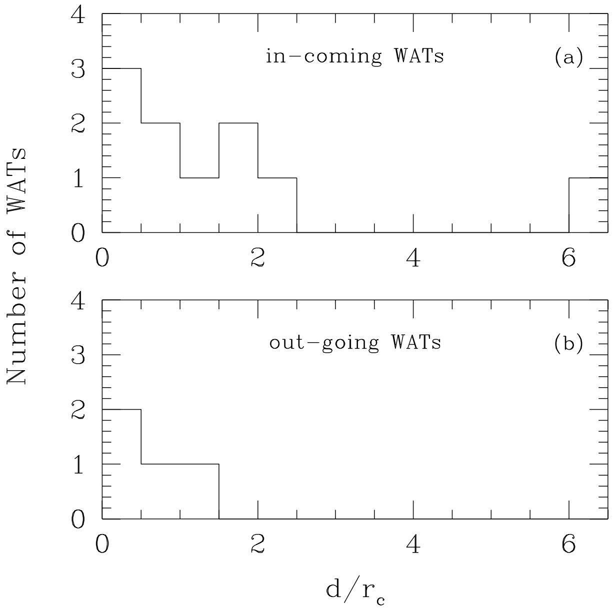

Figure 5. The distribution of distances from the cluster centre: (a) for in-coming sources; and (b) for out-going sources.

rately and objectively the X-ray centres and sizes of the clusters that host the WATs.

The basic findings of this analysis are as follows:

(i) WATs are not generally located at the centres of their host clusters as defined by their X-ray emission. They are found over a range of distances from the cluster centre, out to several core radii.

(ii) If their bent shape can be attributed to ram pressure, then WATs are found to lie preferentially on radial orbits.

(iii) There are more WATs travelling toward the centres of their host clusters than there are systems moving away from the centres.

(iv) There are indications that WATs travelling toward the centres of clusters lie at larger radii on average than those travelling outward.

These findings are exactly what one would expect if WATs are created by mergers between clusters. Specifically:

(i) When two clusters merge, the D/cD radio galaxy that would initially have lain at the centre of one of the merging systems will no longer be at the centre of mass. Whatever the localized impact of the collision on the X-ray emission, one would not expect to find the WAT near the new X-ray centroid.

(ii) In such a merging system, the radio galaxy will continue to move in the direction that its host cluster was travelling in prior to the merger. Such mergers will largely arise from the gravitational attraction between the two pre-existing clusters, resulting in a head-on collision. The radio galaxy will therefore travel along the line joining the centres of the two merging systems. In terms of the merged system, it will therefore initially be moving toward the new cluster centroid, on a radially infalling orbit. The X-ray emission will be somewhat disturbed by the merger process, but, as we have discussed in §4.1, the centroid of the emission will be shifted by very much less than the new cluster's core radius. Since the typical distances between the cluster centroid and the infalling WAT are at least comparable to the core radius (see Fig. 2), this shift is pretty much negligible, and we would expect to see the galaxy's radio jets bent away from the X-ray centroid. Perhaps the best argument for the validity of the way in which the centroid has been estimated comes from Fig. 3: if the adopted cluster centres were in error to the point that they had no physical meaning, then comparison with the independently-derived WAT morphologies could never lead to the correlation shown in this figure.

(iii) Near the new cluster centre, the gas density will be high, and there will be a complex structure of shock-heated gas and turbulence due to the collision. Such an environment will prove very hostile for the relatively fragile radio jets, either destroying the jets entirely or disrupting them to a point where the system is no longer identified as a symmetric WAT. The destruction of a significant fraction of WATs as they pass near the cluster centre explains the imbalance between the numbers of in-coming and out-going systems.

(iv) The D/cD galaxy that host a typical WAT is so massive that dynamical friction will play an important role, even on the galaxy's first passage through the merged cluster's centre. For example, in their numerical simulations of cluster formation through heirarchical mergers, Frenk et al. (1996) found that massive infalling galaxies with typical initial velocities in excess of $900\,\mathrm{km\,s^{-1}}$ were slowed to a mere $\sim 200\,\mathrm{km\,s^{-1}}$ on their first passage through the cluster core [see Frenk et al. (1996) Figure 9; for example, their galaxy 3]. Such decelerated infalling galaxies will not travel back out to anything like the radius from which they initially arrived [see Frenk et al. (1996) Figure 8], explaining the difference between the mean radii of the in-coming and out-going WATs. It is also notable that velocities of a few hundred kilometres per second in the typical gas density near a cluster core are exactly what one needs to bend a radio source into a WAT [see, for example, Sakelliou et al. (1996)].

This analysis therefore provides very strong support for the hypothesis that the morphology of a wide angle tail radio source results from ram pressure against the surrounding intracluster medium, and that the impetus for the radio galaxy's motion has come from a recent cluster merger.

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APPENDIX A: NOTES ON INDIVIDUAL SOURCES

Abell 160: The X-ray structure of this cluster is irregular, showing distinctive condensations. From early *Einstein* observations these clumps of X-ray emission have been identified with emission from the cluster's galaxies. The *ROSAT* HRI image reveals the same situation. The definition of the X-ray centre is rather difficult, even after the removal of the bright point sources. The present data do not permit the calculation of the core radius, since the β-model does not provide a good fit to the surface brightness distribution of the ICM. Additionally, the jets of the radio galaxy are not severely bent, a fact that indicates the lack of a very dense ICM.

Abell 400: This cluster hosts the extraordinary radio source 3C 75, which consists of a dumbbell pair of radio galaxies. The jets of both radio galaxies are bent in the same direction, suggesting that they are both bent by the same cause. The interpretation of Balcells et al. (1995) that this source is the result of a merger of two different clusters, where each cluster hosted one radio galaxy does not look plausible. In such a scenario it is difficult to explain the bending of the jets in the same direction. This source is treated as one radio galaxy in the present survey.

Abell 569: The PSPC image is dominated by the emission from galaxies and point sources. The distribution of the cluster's ICM is not clearly revealed.

Abell 690: The cluster and radio galaxy lie underneath the rib suport structure of the PSPC detector.

Abell 1552: This cluster lies behind the Virgo cluster. Therefore, its X-ray emission is contaminated by the emission from the ICM of the Virgo cluster. The cluster centre reported here coincides with the position of the brightest galaxy of the cluster. This galaxy is also a radio galaxy, and the radio maps (Owen & Ledlow 1997) show that its jets are not distorted, which implies that the galaxy is not in motion relative to the ICM. An attempt to fit only the southern part of the cluster with the β-model yielded inconsistent results, and therefore, a measurement of the core radius cannot be provided.

Abell 1763: The redshift of this cluster that has been extensively used (0.187; Struble & Rood 1991) was originally calculated using the redshift of only one galaxy (Noonan 1981). Recently, Owen, White & Thronson (1988) and Owen, Ledlow & Keel (1995) have measured the redshift of the galaxy that hosts the WAT and find it to be 0.2278, which is the value that is used here. The cluster centre that is reported here is the peak of the X-ray emission.

Abell 1890: The X-ray emission from this relatively poor cluster appears to be clumpy in this short HRI observation.

Abell 2214: This cluster is clearly bimodal. Thus, a calculation of the cluster centre would be misleading. Both peaks of the X-ray emission are used for the definition of the cluster centre. However, the choice of a cluster centre does not influence much the value of the angle θ, since the position of the WAT is nearly aligned with both peaks.

Abell 2220: This cluster appears bimodal in the *ROSAT* image. Apart from a peak of X-ray emission that coincides with the galaxy that hosts the WAT, there are two more aligned peaks of X-ray emission. The position of the middle peak coincides with a big (non-active) galaxy which belongs to Abell 2220, while the eastern peak does not have any pronounced optical counterpart in the Palomar plates. For this reason, the middle peak is adopted as the cluster centre. In any case, this choice for the cluster centre does not influence the measurement of the angle θ, since both peaks are aligned with the position of the galaxy that hosts the WAT. Additionally, the present selection puts the WAT nearer to the cluster centre.

Abell 2304: The calculated cluster centre coincides with the peak of the X-ray emission.

Abell 2306: The X-ray image is clumpy.

Abell 2634: A detailed study of the hot gas context of this cluster, and investigation of the mechanisms responsible for the features of the radio jets of 3C465 can be found in Sakelliou & Merrifield (1998a), Schindler & Prieto (1997), Sakelliou & Merrifield (1998b).

Abell 2637: There is no sign of X-ray emission from the cluster in the available X-ray image.