SEARCHING (THE) FIRST RADIO ARCS NEAR ACO CLUSTERS

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Abstract. Gravitational lensing (GL) of distant radio sources by galaxy clusters should produce radio arc(let)s. We extracted radio sources from the FIRST survey near Abell cluster cores and found their radio position angles to be uniformly distributed with respect to the cluster centres. This result holds even when we restrict the sample to the richest or most centrally condensed clusters, and to sources with high S/N and large axial ratio. Our failure to detect GL with statistical methods may be due to poor cluster centre positions. We did not find convincing candidates for arcs either. Our result agrees with theoretical estimates predicting that surveys much deeper than FIRST are required to detect the effect. This is in apparent conflict with the detection of such an effect claimed by Bagchi & Kapahi (1995).

1. Motivation and Theoretical Expectations

The first gravitational lens (GL) was found upon identification of the “double” quasar 0957+561 [14]. Later, the first lensed images of extended optical objects were discovered as the “giant arcs” [11], and since then CCD imaging of lensed galaxies behind galaxy clusters has turned into an “industry”. This allowed both mapping of the clusters’ gravitational potential as well as unprecedented insight into high-z galaxies, due to the clusters acting as natural gravitational “telescopes” [13]. Up to now, no radio arcs in clusters have yet been identified, although radio searches have yielded more than half of all confirmed cases of “strong lensing” [6]. Compared to optical galaxies, radio sources are rare (their sky densities are comparable for S1.5 ~0.1 mJy and B1 ~24.0 mag), and they are more extended and complex, making it difficult to distinguish lensed from unlensed sources.

We have the highest chance to see radio arcs in massive, centrally condensed clusters at z~0.15–0.6. These tend to be very rich, X-ray luminous, and of mor-
phologically “early” type BM I or RS cD. In the absence of large-area samples of distant \((z \gtrsim 0.3)\) clusters, we chose our lens candidates from the ACO [1] catalog and the sources from FIRST [15], the highest-resolution \((5.4''\)) large-area radio survey available, with a high source density \((\approx 3 \times 10^5 \text{ sr}^{-1} \text{ for } S > \sim 1 \text{ mJy at } 1.5 \text{ GHz})\).

The simplest estimate of \(N_l\), the number of radio sources expected to be strongly lensed by clusters, may be derived from the formula for the Einstein radius \(\theta_E\), the characteristic angular separation from the lens-observer axis within which giant arcs and multiple imaging occur:

\[
\theta_E^2 = 4 G \frac{M_E}{c^2} \frac{d_L}{d_s} \frac{d_s}{d_L} - 1
\]

where \(G\) is the gravitational constant, \(M_E\) is the cluster mass within a radius \(d_L\) \(\theta_E\) from the cluster core \((M_E \sim 10^{14} \text{ M}_\odot)\), \(c\) is the speed of light, \(d_L\) and \(d_s\) are the angular-diameter distances to the lens and to the source, and \(d_L\) is the distance between lens and source. A rough estimate of \(N_l\) is then

\[
N_l \approx (G M_E H_0 c^{-3}) \langle z_i^{-1} \rangle N_{cl} A_s \approx 1.6 \times 10^{-9} \langle z_i^{-1} \rangle N_{cl} A_s
\]

where \(H_0 = 100 h_{100} \text{ km/s/Mpc}\) is Hubble’s constant, \(N_{cl}\) the number of “suitable” clusters and \(z_i\) their redshifts, \(\langle .. \rangle\) is the average, and \(A_s\) the surface density of “suitable” radio sources. Taking the 60 richest \((R \geq 2)\) ACO clusters with \(z \geq 0.1\) covered by FIRST, we have \(\langle z_i^{-1} \rangle \approx 6\). The 585 sources within 1 Abell radius \((1 R_A = 1.5 h_{100} \text{ Mpc})\) imply a surface density of \(\sim 5 \times 10^5 \text{ sr}^{-1}\). Thus we have \(N_l \sim 0.3 \text{ k}\), where \(k \approx 0.3\) is the estimated fraction of distant FIRST sources with compact details, i.e. “suitable” for lensing. We obtain \(N_l \approx 0.1\), or at most \(N_l \approx 1\) if we include all 373 ACO clusters covered by FIRST. For a statistical detection of arc(let)s in ACO clusters we need a survey reaching a limiting flux of \(\leq 0.1 \text{ mJy}\).

Other, more detailed estimates [16] agree that any giant radio arcs in ACO clusters should be below the flux limit of FIRST. Despite of this, a statistical GL effect was claimed to have been detected in a VLA snapshot survey of 46 distant \((D \geq 5 \text{ or } z \geq 0.1)\), cD-type ACO clusters at 1.5 GHz and HPBW=30'' [4]. Within \(d_A = 0.25\) of 28 clusters (where \(d_A\) is the projected distance from the cluster centre in units of \(R_A\)) 40 resolved sources of deconvolved size \(8'' - 35''\) were found. Let \(\phi\) be the acute angle between the radio source major axis and the line joining the radio centroid with the optical cluster centre, i.e. \(\phi = 0^\circ\) for “radial” and \(90^\circ\) for “tangential” orientation. The distribution of this “orientation angle” \(\phi\) of the 40 sources peaked near \(65^\circ\) \((\phi_{med} = 61^\circ \pm 5^\circ)\). This preference for tangential source orientations was notable out to \(d_A = 0.7\), i.e far beyond typical Einstein radii, and was interpreted by [4] as likely due to lensing. If confirmed, this would suggest that the above estimates were pessimistic in that massive, extended dark haloes in clusters are much more frequent than hitherto assumed.

We tried to measure this effect more accurately and cross-correlated the ACO catalog with the 96 May 28 version of FIRST (138,665 sources; \(\alpha, \delta = [6.6^\text{h}..17.6^\text{h}; +28.2^\circ...+42.0^\circ]\). We also looked for individual candidate radio arcs in FIRST. FIRST’s angular resolution is five times better, but with \(\sigma \sim 0.15 \text{ mJy}\) its sensitivity for sources \(\gtrsim 10''\) is worse than that of [4]. Among the 373 ACO clusters covered by FIRST there are 28 cD-clusters. Nine of these clusters contain 29 extended FIRST sources with \(d_A < 0.25\), with deconvolved sizes from \(2''\) to \(14''\).
2. Methods and Results

We find ~9200 FIRST sources (of any shape and flux) within 1 R_A of all ACO clusters. Their centre positions were taken from [1], and Abell radii from [3]. Within 0.55 R_A of 334 different clusters we find ~700 sources more than randomly expected, i.e. one or two genuine cluster members per Abell cluster, depending on the amount of complex sources broken up into components in the FIRST catalog.

The FIRST catalog lists deconvolved major (θ_a) and minor (θ_b) axes and a radio position angle (PA) for every source. Both θ_a and θ_b may be negative whenever the effect of noise yielded a source fit smaller than the beam. We discarded 33% of all FIRST sources: 26% had θ_a < 1" or else θ_a = θ_b, i.e. were either too small or “too round” to trust their orientation. Another 7% had θ_b < 0 and |θ_b| > |θ_a|, i.e. PA was ill-defined. For each FIRST source located within 1 R_A and having a significant radio PA we calculated its orientation angle φ as defined in Section 1.

Before fine-tuning our sample for the search for radio arcs we selected those FIRST sources with peak flux S_p ≥ 2 mJy and axial ratio ε = θ_a/θ_b ≥ 1.5 in clusters with distance class D ≥ 5. We then compared the distribution of φ for the 1065 sources with d_A ≤ 0.75 in 269 different clusters, and those of the 258 sources with d_A ≤ 0.25 in 130 clusters. Both samples were split into three equal parts, the first one at d_A = 0.33 and 0.56 (Fig. 1a), and the second one at d_A = 0.10 and 0.18 (Fig. 1b). Histograms for the inner (solid lines), the middle (dashed lines) and the outer annuli (dotted lines) around cluster centres show no trend for φ to peak at higher values for sources closer to the cluster cores (i.e. smaller d_A), contrary to findings of [4]. A Kruskal-Wallis test shows that the distributions have probabilities of 25% (Fig. 1a) and 20% (Fig. 1b) of being drawn from the same population of orientation angles. A Kolmogorov test shows that uniformity cannot be rejected at significance levels of ≥10% (~5% for 0.1 < d_A < 0.18).

If the clusters of our sample are similar to those with known optical arcs, then their Einstein radii must be of order 30" to 60". Inaccurate Abell centres in ACO of ~2' rms [1] could potentially invalidate the above analysis and will create random errors in φ, large enough to smooth out a real peak in a φ distribution of sources with d_A ≤ 0.25. In order to minimise this source of error, we defined a subsample of 65 sources with d_A ≤ 0.25 in clusters of type BM<II. The latter have central dominant galaxies and, we assume, both better-defined ACO centres and a higher probability of showing GL. For this sample, and a sub-sample of 25 sources (S_p ≥ 2 mJy, ε ≥ 1.5) we obtain the highest values of ⟨φ⟩ and φ_med of ~50° (Fig. 1c). A Kolmogorov test is unable to reject uniformity at significance levels of 26 resp. 16%.

Errors in ACO’s centre coordinates should be relatively less important for nearer clusters (at least in units of R_A). However, for a sample of 177 FIRST sources (S_p ≥ 2 mJy, ε ≥ 1.5) with d_A < 0.25 in 79 ACO clusters of distance class 4 and 5, we found ⟨φ⟩ = 43° and φ_med = 39°. A Kolmogorov test gives a significance level of 5% for rejection of uniformity. Thus we find no statistical evidence for radio arcs in Abell clusters in the FIRST survey, neither by selecting clusters by their distance, richness, or morphological type, nor by selecting radio sources by their proximity to the cluster centre, their flux or their ellipticity.
3. Are there really no Radio Arcs in FIRST?

Considering that the source sample will anyway be contaminated by many of the elongated, tailed, FR I type sources typically found in clusters, we tried to find potential arc candidates by inspection of maps of individual sources. Using the cluster database maintained at Astronomical Institute of St.-Petersburg University [5] we examined the FIRST and Digitized Sky Survey (DSS) images and APM charts [10] for two subsamples. We looked at all 42 FIRST sources with $d_A < 0.2$, $D \geq 5$, $S_p \geq 2$ mJy, $\epsilon \geq 1.5$, and $\phi \geq 70^\circ$. One of these sources (4C 39.29) stands out due to its high flux ($S_{1.5} = 1.4$ Jy). It is located 2.7′ ($d_A = 0.3$) SE of the cD in A 963, a rich X-ray cluster at $z_{\text{cl}} = 0.21$, which is known for its giant optical arcs within ~20′′ N and S of the cD [7]. Unpublished high-resolution VLA maps [8] suggest independently that the source may be lensed. The next strongest candidate (4× weaker) is a wide-angle-tail (WAT) source close to the X-ray centre of A1190, previously mapped by [12]. The FIRST and DSS images for this and several other sources revealed that either the radio PAs refer to subcomponents of more complex sources, or that $\phi \geq 70^\circ$ is due only to poorly defined Abell centres, or both.

Two examples are given in the upper panels of Fig. 2: a 3C 465-type WAT source in A1438 ($z_{\text{est}} = 0.16$, R=1, BM=III), and a complex WAT in A2110 ($z_{\text{cl}} = 0.1$, R=1, BM=I-II), probably seen nearly end-on. Both have prominent parent galaxies.
We also inspected about 150 sources in 65 clusters with $R \geq 2$ and $z > 0.1$ which may be more likely to contain radio arcs. We determined improved cluster centres from DSS images, but found no preference for a “tangential” orientation ($\phi > 45^\circ$) of unidentified (presumably background) radio sources around these revised centres. Moreover, we find that most of the sources seen towards the cluster cores can be identified with likely cluster members or other galaxies, leaving a very poor statistics for the remaining unidentified radio sources. We note that [4] had only excluded the cD galaxies as cluster members from their analysis.
The lower panels of Fig. 2 show two sources with intriguing shapes. The cD galaxy in the southern clump of the rich (R=2, BM=III) X-ray [2] cluster A1033 ($z_{cl}$=0.1) is $\sim$ 3' ($d_A=0.22$) SE from the ACO centre, much further than the characteristic Einstein radius ($\sim$45''). Close to the cD (which is also the X-ray centre) there are two FIRST radio sources, both having their major axes perpendicular to the radius vector from the cD. A much deeper 1.4 GHz map [9] shows the arc-like source due W to be a head-tail source in the cluster. However, its high surface brightness and abrupt termination of the tail are unusual. The southern source has a very steep spectrum and lacks an optical identification. It has been interpreted as a cluster radio halo [9], but with its 100''×100'' arc-like shape [9] it is equally unusual and merits further study. The source in A 876 ($z_{est}=.17$, R=1, BM=II:) drew our attention due to a radio “arc” connecting two compact sources $\sim$25'' apart. However, the “arc” is curved away from the cluster centre and almost certainly due to the inner, smoothly-curved jets of a WAT source coinciding with a likely cluster member ($m_{APM}^R=17.3$).

4. Discussion

The typical offsets of Abell centres from the true centres of mass are usually larger than typical Einstein radii. This is true at least for distant clusters and particularly if we consider the subcluster centres of F-type and other clusters as distinct cluster cores. Thus, poor Abell centres alone prevent us from finding statistical GL, and extending the same statistical analysis to a larger number of clusters would not remove this obstacle. Our analysis of individual objects proves that a statistical source selection by catalog parameters (like BM, RS, $d_A$, $\phi$, $\epsilon$, etc.) is insufficient for finding good arc candidates.

An inspection of FIRST and DSS images of large numbers of sources near accurately known cluster centres may discover one or two radio arcs; however, the theoretical predictions indicate that we need an order of magnitude increase in brightness sensitivity over that of FIRST before the number of radio arcs can approach those discovered in the optical domain. This is best achieved by deep radio mapping of small samples of distant, X-ray luminous clusters with accurate centres of mass determined from X-ray maps.

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