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THE USE OF RADIO SOURCE MORPHOLOGY IN DETECTING CLUSTERS OF GALAXIES ASSOCIATED WITH QSOs

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ABSTRACT

Recent work strongly indicates that some types of morphological distortion of double radio sources occur only in sources associated with galaxies which are members of clusters. We therefore suggest that QSOs possessing similar distortions in their radio morphologies are also associated with clusters of galaxies. From available data we have determined that 3C 47, 3C 323.1, 3C 351 (all QSOs), and 3C 61.1 (possibly a QSO) all have radio morphologies indicative of cluster membership. Two of these objects, 3C 323.1 and 3C 61.1, are known to be members of clusters, and our observations indicate that 3C 47 may have an associated cluster. We suggest that investigation of QSOs with distorted radio morphologies would provide a sample of distant clusters of galaxies at known redshifts, allowing study of galaxy evolution, cluster X-ray source evolution, and possibly an accurate determination of q_0.

Subject headings: galaxies: clusters of — quasars — radio sources: general

I. INTRODUCTION

Identification of rich clusters of galaxies associated with QSOs would have considerable impact on our understanding of QSO evolution (van den Bergh 1975). Most important, it would be possible to determine directly whether QSO redshifts are cosmological. Accordingly, numerous statistical analyses of positional correlations between QSOs and clusters have been undertaken, most recently by Roberts, O'Dell, and Burbidge (1977). They conclude that low-redshift QSOs ($z \leq 0.2$) are less frequently associated with rich Abell clusters than are 3CR galaxies. This result contradicts the hypothesis that QSOs are related to the giant elliptical galaxies identified with many 3CR extended sources.

Observational studies designed to establish physical relationships between individual QSOs and clusters of galaxies have identified a half-dozen examples (Battistini *et al.* 1975, and references therein). In none of these cases is the QSO found at the center of a rich cluster, although Butcher *et al.* (1976) discovered a rich, distant cluster centered on 3C 66A, a BL Lacertae object. It therefore appears likely that a majority of QSOs with small redshifts are not associated with clusters of galaxies.

Observational attempts to identify clusters associated with QSOs are therefore likely to be largely unsuccessful, while consuming a great deal of large telescope time. Such observations would be greatly facilitated if QSOs likely to be associated with clusters could be identified.

Guthrie (1977) has attempted to use radio spectral indices to identify QSOs likely to be in clusters. Noting that, for radio galaxies, large spectral indices are primarily associated with cluster galaxies, he investigated the spectral indices of QSOs (corrected to their rest frames). He found no examples of extremely steep radio spectra and therefore could not identify QSOs likely to be associated with clusters. He notes, however, that "The absence of steep spectra among quasars does not necessarily mean that quasars never occur in rich clusters of galaxies, since quasars are probably being observed only in their early high-luminosity phases." We must therefore look elsewhere for a reliable cluster indicator for QSOs.

In this *Letter* we use radio maps of QSOs to identify those distorted by interaction with the "intergalactic medium." Radio galaxies displaying such distortions have (thus far) been found only in clusters. If clusters of galaxies associated with these QSOs can be identified, study of distorted radio sources will provide both information on QSO evolution and a convenient means of detecting distant, rich clusters of galaxies which may be associated with QSOs at higher redshifts.

II. MORPHOLOGY OF CLUSTER RADIO SOURCES

Recent statistical studies of extended radio sources in clusters of galaxies indicate that at least two-thirds of those sources are morphologically distorted (i.e., the sources do not display the classical "straight" double source geometry). For example, Burns and Owen (1978)

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found that "the average misalignment between double source components . . . [with respect to] the parent galaxies is greater in clusters than out." Also, Rudnick and Owen (1977) have discussed the opening direction of seven **C** shape sources in clusters and find that for all seven sources the **C** opens away from the cluster center.

The above effects can be simply explained as the result of interactions between the intracluster medium (ICM) and ejected radio components. It is generally assumed, as suggested by Harris (1974), that the **C** and **S** distortions are due to interactions between gas in the ejected radio components and a low-density medium surrounding the central galaxy. Detailed studies of these interactions have been pursued, e.g., by Christiansen (1978) and Christiansen and Scott (1977). The major facets of such analyses can be summarized for our purposes (medium = ICM) as follows: When two components are ejected in opposite directions from a parent object into an extended low-density medium, the plasma is confined by the ram pressure of the medium. If the components are traveling in a homogeneous medium (or if the components are ejected radially from the central point of a medium with a spherically symmetric density distribution), a "straight double" results. In general, however, components ejected from a cluster galaxy will not initially have velocity vectors parallel to the direction of the ICM density gradient. In this case, the radio components experience a force due to the resultant gradient in ram pressure across their surfaces. The component trajectories will therefore curve so as to eventually parallel the density gradient. In short, the components turn toward the direction of lowest density, following the path of least resistance, and a **C** or **S** distorted morphology results. In extreme cases, the optical object will be detectably displaced from a line connecting the radio lobes.

If, on the other hand, the ejection axis is approximately parallel to the medium-density gradient, the component trajectory curvature should be negligible. However, unless the optical object is located at the center of the ICM, one radio component will travel toward higher-density regions, the other toward lower. The former component will be more effectively confined by the ICM and therefore should appear brighter, smaller, and closer to the parent object than will its "low-density" companion. Unfortunately, grossly unequal masses in the ejected components might produce a similar phenomenon, so observational verification of large component brightness ratios as a cluster phenomenon is required.

We can compare the expected ICM distortion effects with the available observational data. The large percentage of cluster sources found to be distorted by Rudnick and Owen (1977) and Burns and Owen (1978) is, of course, immediately explained, as is the higher frequency of distortions in cluster sources compared with field sources (Burns and Owen 1978). The **C** distortions and consequent displacement of the central object from the lobe-lobe axis can arise when the parent galaxy is off-center in a spherically symmetric ICM. The radio components will both curve away from the cluster center in precisely the manner Rudnick and Owen (1978) observed in the seven **C**-shaped sources they studied. Distortion is avoided only when the component ejection is parallel to the local ICM density gradient. In that case we expect that the component headed toward the cluster center will become brighter than its companion, as noted in some cases by Burns and Owen (1978).

We therefore suggest that, in the search for clusters of galaxies associated with QSOs, the most promising objects for study are those possessing extended double (or triple) radio components which display central source displacement and/or the **C** or **S** distortion. Those QSOs possessing double radio sources with one component considerably brighter than the other may also be of interest.

III. QSO RADIO CHARACTERISTICS

We now consider the available QSO radio data in light of the above suggestion. Definite detection of the source distortions discussed above requires excellent resolution, detailed radio maps, and accurate radio and optical positions.

The most reliable cases of ICM interaction, QSOs off-axis with respect to the line between radio lobes, are difficult to identify with certainty. A comparison of radio component positions with the optical positions of the QSOs will often merely isolate cases of zero-point errors in the positions. We have therefore concentrated on those observations revealing third, central components which are normally assumed to coincide with the optical object. When the central radio component and optical object both appear displaced with respect to the line between the outer lobes, and the lobes have off-axis tails, we consider the distortion well established.

Uneven component luminosities are much more easily detected, of course, but may also be due to ejection asymmetries. Therefore we consider such objects likely cases of ICM interaction only if off-axis component "tails" and a difference in the sizes of the two components can also be identified.

As selection of a distorted source sample is to some extent a matter of judgment, we first consider an independent sample, Harris's (1974) original collection of distorted sources. Harris lists 37 distorted 3C sources, including three QSOs (3C 47, 3C 323.1, 3C 351) and one source possibly associated with a BSO in a cluster (3C 61.1). For two of these objects, deep photographs are available. Direct photographs of 3C 61.1 published by Longair and Gunn (1975) show a cluster ($z = 0.185$) which apparently contains both the radio source and a BSO ($z = 0.184$) (Miller, Robinson, and Wampler 1973). The radio source exhibits **S** distortion, as expected for a cluster source, and the position of the low-frequency bridge between the radio lobes indicates that the radio source is associated with either the BSO or a cluster galaxy 9″ closer to the radio lobe axis. As the lobe separation is large, the identification remains uncertain, although we note that spectroscopic observations detected no emission lines in the galaxy.

Considerably more excitement is provided by 3C

323.1 ($z = 0.264$), a well-known QSO whose radio structure (Branson *et al.* 1972; Pooley and Henbest 1974) shows a triple source with a well-developed off-axis tail on one component and a possibly off-axis central object. Further, the northeastern radio component is considerably brighter and closer to the QSO than the southwestern. From these two characteristics we expect that the ICM density increases, generally, northward. It is interesting, therefore, that Oemler, Gunn, and Oke (1972) suggest that 3C 323.1 is a member of Zw Cl 1545.1+2104, a cluster with $z = 0.27$ centered $6\rlap{.}'5$ NW of the QSO. The cluster isopleths presented by Oemler *et al.* indicate that the distortion opens generally away from the cluster center and the QSO may be displaced toward the cluster center, in keeping with our predictions. Further, Oemler *et al.* report a galaxy density enhancement N of the QSO. If the ICM is similarly enhanced in that region we would expect the NE radio component to be brighter than the SW component, as well as closer to the QSO. The radio observations also confirm these expectations. We therefore conclude that these observations strengthen the arguments for 3C 323.1 as a cluster member and support our contention that distorted QSO radio structure is an indication of cluster membership.

The radio sources associated with other QSOs reported to be cluster members (Battistini *et al.* 1975, and references therein) are either unmapped or unresolved, as is 3C 48, for which Sandage and Miller (1966) could detect no associated cluster.

A study of available QSO radio maps was made to isolate other favorable cluster association candidates. We found that the two remaining QSOs in Harris's (1974) original paper, 3C 47 ($z = 0.425$) and 3C 351 ($z = 0.37$), were the best available examples of the two types of distortion. The object 3C 351 is an extreme example of the uneven component brightness phenomenon. The northern component is much brighter and somewhat more compact than the southern, and has an off-axis "tail." All of these traits, of course, would be expected if 3C 351 is a cluster member, and this QSO should provide an interesting test of the suggestion that uneven lobes are a cluster phenomenon.

The distortion in the radio morphology of 3C 47 is the greatest observed among well-studied QSOs. The radio maps reveal a triple source with strong **S** distortion (very well developed, off-axis component tails) as well as a central source, coinciding with the optical object, which is displaced about 3″ northwest of the axis of the outer lobes (Branson *et al.* 1972; Pooley and Henbest 1974). This indicates that 3C 47 is associated with a cluster centered slightly north or northwest of the QSO, and which may be somewhat flattened (causing the **S** shape).

A plate of the 3C 47 field was secured for us by T. Boroson, using the 40 mm ITT image tube on the Steward Observatory 90 inch (2.3 m) telescope. An RG 630 filter and 127-04 plate were used in the 20 minute exposure, which revealed a group of objects not visible on the Palomar E plate around the QSO. A portion of the image-tube plate is reproduced in Figure 1 (Plate L2).

Comparison of this figure with the finding chart published by Penston, Penston, and Sandage (1971) shows that the object 20″ NE of the QSO is visible, but faint, on the Palomar E plate, implying $m \sim 19.5$. The seven objects with $m > 20$ found within a 50″ radius of 3C 47 have magnitudes compatible with the distance implied by the QSO redshift.

Counts of objects fainter than 20th mag in 50″ square boxes on the image-tube plate yield an average of 1.2 ± 0.9 objects per box, while the box centered on the QSO contains five objects. One of the other boxes contains three objects; each of the remaining 26 boxes contains two or less. It is therefore likely that the faint objects near 3C 47 form a cluster of galaxies associated with the QSO. Note that the center of the apparent cluster is slightly north of the QSO, as predicted from the radio data.

Therefore data for three of the four objects in our restricted QSO sample indicate that distortions in the radio morphologies of QSOs can be caused by the ICM in clusters of galaxies associated with the QSOs.

Finally, we suggest that distortions in their radio maps indicate that 3C 263 (Pooley and Henbest 1974) and B2 1222+32 (Fanti *et al.* 1977) are worthy of further study. The radio map for the latter appears to indicate a **C** distorted triple with the central component well off-axis. The position of the optical object identified as the radio source by Fanti *et al.* is, however, well away from the central component. If further observations brought the optical identification and central component into coincidence, cluster membership of the radio source would be indicated.

IV. SUMMARY

On the basis of our detection of an apparent cluster of galaxies associated with 3C 47 and similar cluster–QSO associations reported previously for 3C 323.1 and 3C 61.1, we suggest that radio source distortions can be used to identify QSOs which are associated with clusters of galaxies. Deep direct plates of 3C 351 and B2 1222+32 would provide a further test of this suggestion.

If further QSO–cluster associations can be identified at larger redshifts and the evidence continues to support the cosmological interpretation of QSO redshifts, the QSOs and associated clusters would be useful in several types of astrophysical investigations. With the QSOs providing accurate redshifts out to substantial distances, observations of the associated cluster galaxies would allow study of galaxy evolution, cluster X-ray source evolution, and, possibly, an accurate determination of q_0.

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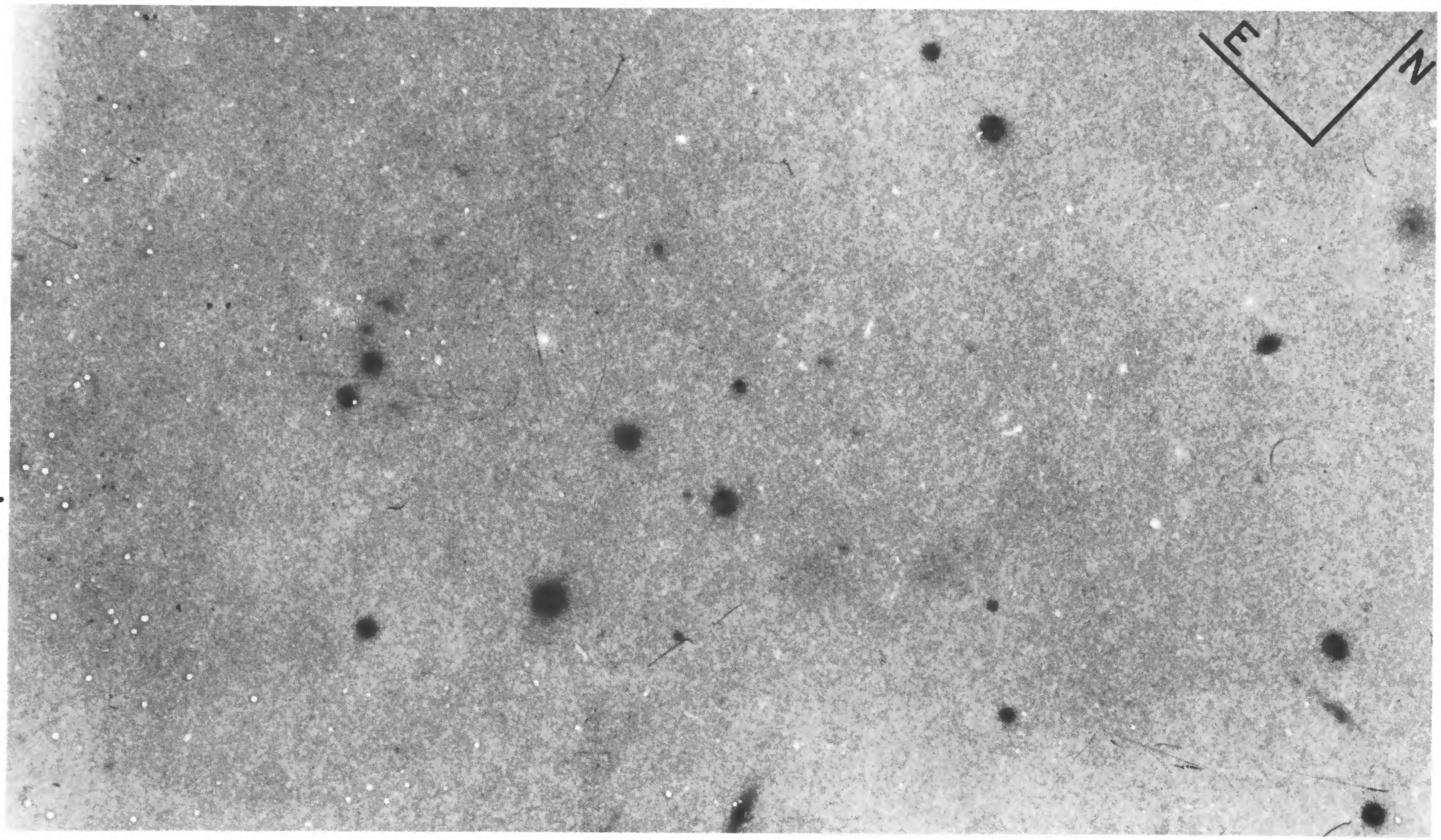

Fig. 1.—Photograph of the 3C 47 field, taken with a 40 mm ITT image tube and RG 630 filter (6400–8500 Å) on 127-04 emulsion. The field shown is 2′.2 by 3′.7. The object 3C 47 is marked by line segments.

Hintzen and Scott (*see* page L49).

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