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# Active Galaxies with Radio Trails in Clusters

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**New radio data and a critical examination of the interacting galaxies hypothesis to explain complex radio sources in clusters lead us to reject a causal relation between sources in clusters. Instead, the "head–tail" radio galaxies are proposed to represent radio trails of galaxies, active in their own right, along trajectories through a dense intergalactic medium.**

HERE we describe some of the data obtained recently with the Westerbork synthesis radio telescope (WSRT) in an observing programme aimed at radio sources in clusters. We examine the hypothesis that the energy of certain peculiarly extended sources in a cluster originates in another, more compact radio source, sometimes hundreds of kpc away, and present radio evidence bringing new features to light which have a bearing on these problems. This leads to an alternative interpretation which avoids the many difficulties besetting the "interacting galaxies" hypothesis and yields information about a cluster's intergalactic gas density.

## The Perseus, Coma and 3C129 Clusters

Ryle and Windram[1] investigated the Perseus cluster with the Cambridge One Mile Telescope at 408 and 1,407 MHz. They measured the brightness distribution of radio sources identified with NGC 1265 and IC 310, both roughly half a degree from the active Seyfert galaxy NGC 1275, and found that these weak radio galaxies have "head–tail" radio configurations, with the optical object at the front of the head and the tail pointing away from the direction of NGC 1275 (=3C84A) to within about 15°. All three radio sources are enveloped by a large low surface brightness source (3C84B). Ryle and Windram concluded that the radio sources of NGC 1265 and IC 310, weaker than 3C84A by factors of $\times 3$ and $\times 25$ respectively, are formed by energy transported from the active galaxy. In particular they chose a model where a relativistic particle stream, emitted from NGC 1275 over a large solid angle, interacts with the gaseous component of the galaxies encountered. The magnetic field in the latter then ensures both the dynamic coupling and the nonthermal radio emission.

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Willson[2] studied the Coma cluster and showed that it contains a pair of radio sources whose radio morphology, relative position and orientation are somewhat similar to the source pair associated with NGC 1275 and 1265. In this case the more compact source, 5C4.85, is four times *weaker* than the extended source 5C4.81. The tail points about 45° away from the line joining compact and extended source, in conflict with the simple model's prediction. Willson showed that this may well be explained by the relative motion of the galaxies during a few times $10^7$ yr, his estimate of the radio source lifetime.

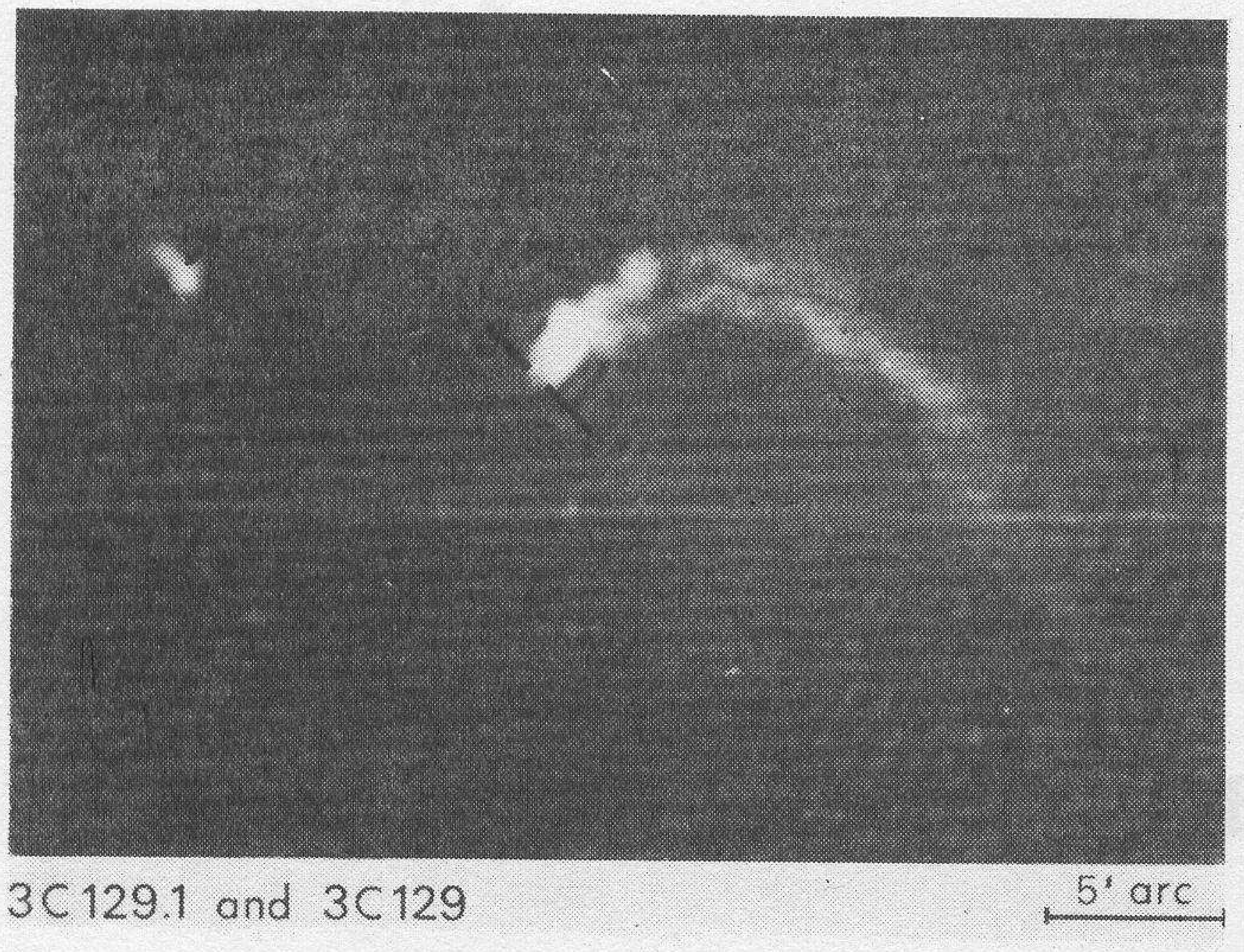


**Fig. 1** 1,415 MHz radiophotograph of 3C129 and 3C129.1. The effective resolution is $22\times31$ arc s; the sensitivity per synthesized beam ($5\times$r.m.s.) is $2\times10^{-29}$ W m$^{-2}$ Hz$^{-1}$. The central depression results from the missing zero and 18 m baselines. Bars indicate the positions of the optical galaxies.

The radio source pair 3C129 and 129.1 has also been mapped with the One Mile Telescope[3], but it lies in an obscured region of the galactic plane and only recently have both members been convincingly identified[4]. Although spectroscopic information is lacking, the estimate based on corrected apparent magnitudes gives a distance comparable with the Perseus and Coma clusters (~50 Mpc). The pair has a radio configuration similar to those discussed above, and Hill and Longair[4] conclude on the basis of a complete set of about 200 3C source maps that these three systems form a separate category in that set. All three are located in rich clusters and are intrinsically weak radio galaxies. Their space density is about one third that of such clusters, a suggestive criterion for further searches with a sensitive high resolution radio telescope. Hill and Longair adopt the Ryle and Windram hypothesis of interacting galaxies, assuming the compact radio source to be the origin of the extended source's energy. Unlike Willson, however, they do not follow the Ryle and Windram model of relativistic particle streams through large solid angles; instead they postulate highly collimated cold plasma streams from the compact to the extended radio source.

## Interacting Galaxies Hypothesis

Several problems associated with the model of Ryle and Windram remain to be explained. For example, there are large spectral differences between the compact and extended sources; a past energy production rate in NGC 1275 much greater than its already large present power and the process of interaction between a stream of relativistic particles and a galactic gaseous component remain to be explained. Several other galaxies in the Perseus cluster, closer to NGC 1275 than the two "head–tail" sources, were not detected as radio sources; this was attributed[1] to less significant gaseous components in these fainter systems which might make them somewhat weaker. For Willson's Coma cluster study this limitation is much more stringent because there the compact source which is the supposed origin of the particle streams is not nearly so dominant a radio source. Hill and Longair attempt to retain the interacting galaxies hypothesis but to accommodate several difficulties Willson already saw: the lack of radio emission from galaxies nearer to the compact source than the extended one and the much greater energy requirements of the compact than of the extended source (for the Coma and the 3C129 pairs the supposed source of all the energy is much the weakest radio emitter). Their arguments, used to account for the double structure of the heads in 3C129 and NGC 1265 and for the discrepancies of tail directions with respect to compact source locations, seem to us entirely *ad hoc*. The descriptive model and flow pattern illustrations invoke many poorly understood processes which add up to a physically improbable and unnecessarily complex system. Even if the cold plasma kinetic energy transport were sufficient, how that could produce the radio sources observed is quite obscure. Comparisons with jets such as that in M 87 or the bridges between the components of symmetric double radio galaxies lend no support to the collimated stream model of Hill and Longair, for, unlike their streams, these features are themselves detectable sources of nonthermal emission.


**Fig. 2** A 1,415 MHz radiophotograph of NGC 1265; resolution $22\times33$ arc s. Otherwise as Fig. 1.

## New Observations at 1,415 MHz

The WSRT is an east–west array of ten fixed and two movable 25 m paraboloids. Each dish has a dual polarization front end at its prime focus and each movable dish dipole is combined with each dipole of every fixed dish, to provide eighty interferometers, four for each of the twenty simultaneous baselines. A complete aperture synthesis consists of $4\times12$ h of data, giving eighty contiguous baselines from 36 to 1,458 m at 18 m intervals. These data are transformed into maps of the four Stokes parameters, which have a tapered sensitivity from the single dish pattern with a 37 arc min diameter at the half-power points and whose definition is provided by the synthesized beam of (22 arc s)×(22 arc s cosec δ). The r.m.s. noise at the field centre is $0.4\times10^{-29}$ W m$^{-2}$ Hz$^{-1}$ for full synthesis with the present receiver system (bandwidth 4 MHz, system temperature 240 K). For such an observation a perfect measurement gives a grating ring at 40 arc min in RA from a source.

The full baseline coverage and the gain and phase stability of the WSRT make it easier to map faint features near strong sources.

NGC 1265 tail is well defined. We presume that the latter lies in a plane which makes a small angle to the line of sight which may be tangential to the last part of the tail.

There is a chain of galaxies between NGC 1275 and IC 310. We detect three of them, one of which has a most interesting structure. It is the 15.4 mag. galaxy designated 15 by Chincarini and Rood[5]. Fig. 3*a* shows a contour map of the object and its surroundings, Fig. 3*b* is a schematic representation of the Seyfert galaxy, the three extended objects and their orientation. The newly detected galaxy has a 1,415 MHz flux density of $30\pm5\times10^{-29}$ W m$^{-2}$ Hz$^{-1}$ and its radio structure resembles that of NGC 1265 and IC 310. The region of maximum brightness has the bright galaxy at its front edge and the pronounced radio tail points, *not away from but nearly towards* NGC 1275.

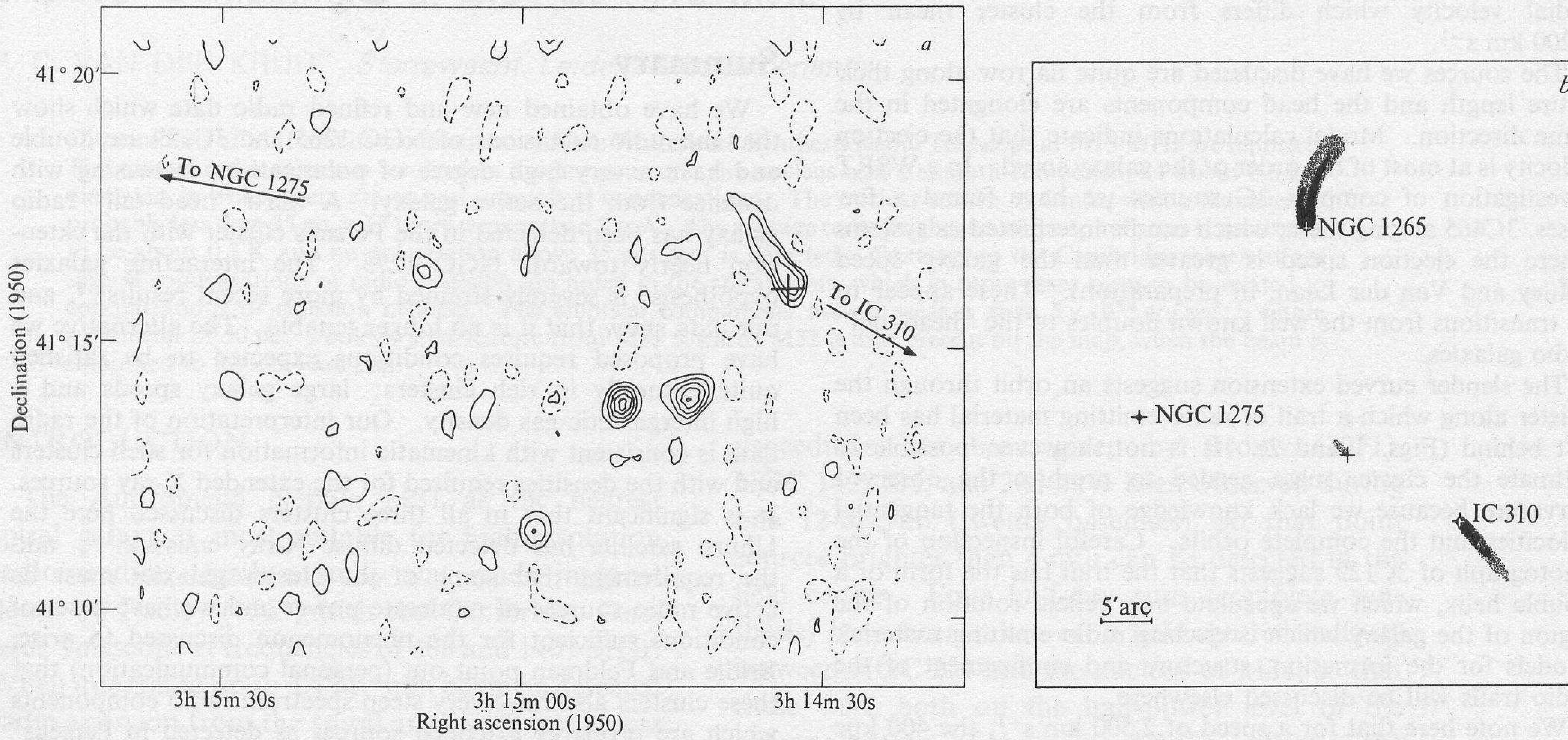


**Fig. 3** *a*, A 15×11 arc min area from the full synthesis map centred on IC 310, showing the radio source associated with galaxy 15 of Chincarini and Rood[5]. Brightness contours are at 2.1 K intervals, excluding the zero level; dashed contours represent negative levels. The cross indicates the optical position. *b*, A schematic representation of NGC 1275 and the active galaxies with radio trails in the Perseus cluster, indicating relative positions and orientations. Crosses mark the optical positions.

Fig. 1 shows a 1,415 MHz full synthesis map of the 3C129/3C129.1 brightness distribution. The radiophotograph is a computer controlled cathode ray tube representation of the 512×512 intensity points in the map. We have found these radiophotographs useful complements to conventional contour maps. The head of 3C129 is double and the tail, not detected in the Cambridge 1,407 MHz map and not resolved at 408 MHz, is also clearly double. It has a length of more than 400 kpc and remains quite narrow. The linear polarization increases progressively along the tail from 5% near the head to more than 60% before it becomes noise limited. These data and their significance will be discussed in detail elsewhere. The structure of 3C129.1 is obscured by a grating ring in the Cambridge 1,407 MHz data; here it is clearly resolved. Its extent is about 2 arc min in a position angle of ~45°. Its structure bears little resemblance to that of NGC 1275, the source presumed to have lit the extended sources in Perseus.

We made two complete synthesis maps of the Perseus cluster, one centred near NGC 1265 and one near IC 310. The former shows that the structure of NGC 1265 is similar to that of 3C129, with a double head and a tail which exhibits double structure and a high degree of polarization. Fig. 2 shows the radiophotograph. We suspect that much of the difference between Fig. 1 and Fig. 2 is a result of projection effects. The tail of 3C129 disappears into the noise, but the end of the

## Alternative Interpretation

The discovery of an object whose tail points in a direction counter to that predicted by the interacting galaxies theory indicates that the approximate alignment of both the NGC 1265 and IC 310 tails along radius vectors from NGC 1275 is fortuitous. In our view this is conclusive evidence that the "head–tail" radio galaxies are not caused by compact radio sources some hundreds of kiloparsecs away. We propose a simpler alternative explanation, namely that the extended sources are radio galaxies in their own right, *causally independent* of any other radio sources in their neighbourbood. The component distortion, the displacement of the optical galaxy to the front edge of the radio brightness distribution and the direction and form of the radio trail all suggest motion of a radio galaxy resisted by a gaseous medium.

What if the extended galaxies under discussion became radio sources by activity in their own nucleus? Apart from their tails, the radio structure of 3C129 and NGC 1265 is reminiscent of common double radio galaxies. According to widely accepted models of these sources, the radio emitting material is ejected from the central region of a galaxy in two comparable, oppositely directed streams, which after emerging from the galaxy are prevented from expanding and dispersing by the dynamic pressure at the radio source boundary. This pressure arises from the inertia of the external medium encountered by the ejected material. We believe that the morphological peculiarities of some radio sources in clusters can be understood in the framework of these "ram pressure theories" (see refs. 6–8), provided the galaxy moves at very high speed through the cluster's intergalactic medium. Evidence that this is the case comes from the investigation of the Perseus cluster; Chincarini and Rood[5] show that the radial velocity dispersion is 1,600 km $s^{-1}$, the largest known, and that NGC 1265 has radial velocity which differs from the cluster mean by 2,200 km $s^{-1}$.

The sources we have discussed are quite narrow along their entire length and the head components are elongated in the same direction. Model calculations indicate that the ejection velocity is at most of the order of the galaxy speed. In a WSRT investigation of complex 3C sources we have found a few cases, 3C465 among them, which can be interpreted as systems where the ejection speed is greater than the galaxy speed (Miley and Van der Laan, in preparation). These appear to be transitions from the well known doubles to the "head–tail" radio galaxies.

The slender curved extension suggests an orbit through the cluster along which a trail of radio emitting material has been left behind (Figs. 1 and 2). It is not, however, possible to estimate the cluster mass needed to produce the observed curvature because we lack knowledge of both the tangential velocities and the complete orbits. Careful inspection of the photograph of 3C129 suggests that the trail has the form of a double helix, which we speculate may reflect rotation of the region of the galaxy which is ejecting radio emitting material. Models for the formation, structure and confinement of the radio trails will be discussed elsewhere.

We note here that for a speed of 2,500 km $s^{-1}$, the 400 kpc trail of 3C129 implies an age of $2\times10^{8}$ yr for the end of the detectable feature. Radiative losses must have affected the spectrum of the trail[9] so at high frequencies it will become undetectable at a smaller distance from the galaxy. Willson found such an effect for 5C4.81 in the Coma cluster. In addition to further high resolution 5 GHz studies we propose to search rich clusters for extended sources. One may expect to find some trails without detectable heads, because the former may persist longer than the galaxy's activity. Such searches are best carried out at low frequencies which are affected least by radiative losses and where the instrumental sensitivity to weak extended features is also much improved.

## Density of the Intergalactic Medium

A striking feature of all five "head–tail" radio sources (three in the Perseus, one in the Coma, one in the 3C129 cluster) is that the optical galaxy lies at the *front edge* of the radio source. In our model the radio source originates in that galaxy but as soon as the radio emitting streams or clouds are exposed to the intergalactic medium their forward motion is resisted. The fact that the radio source front edge lags behind the galaxy implies that the mass density in the radio source is at most a few times the density of the surrounding medium and its velocity is quickly reduced as momentum is conserved. The second important implication of the galaxy's front edge position is that the dynamic pressure exceeds the internal pressure contributed by relativistic particles and magnetic fields in the radio components of the head: $\rho_{i.g.}\, v^2_{ga} \gg p_{radio}$. If this in equality is not satisfied the radio source expands faster then $v_{gal}$ and the radio source front edge will remain *ahead* of the galaxy. The minimum pressure can be calculated from the synchroton emission theory for a source of known brightness and dimensions. The values are of the same order in all cases considered here, $10^{-11} < p_{radio} < 1.4\times10^{-10}$ dyne $cm^{-2}$; the lower and upper estimate are for a relativistic proton contribution equal to or one hundred times that of the electrons, respectively. These are minimum values which will increase if subsequent higher resolution data show the radio components to be more compact. For galaxy speeds as high as 2,500 km $s^{-1}$ the above inequality and these internal pressures lead to lower limits of intergalactic gas densities of $1.6\times10^{-28}$ and $2.2\times10^{-27}$ g $cm^{-3}$. Although precise values require both refined observations and detailed models, the radio structure of these sources unavoidably requires densities of this order. The values are high but not unacceptable for the central regions of rich clusters.

## Summary

We have obtained new and refined radio data which show that the radio extensions of NGC 1265 and 3C129 are double and have a very high degree of polarization, increasing with distance from the active galaxy. A third "head–tail" radio galaxy has been detected in the Perseus cluster with the extension nearly towards NGC 1275. The interacting galaxies hypothesis[1] is severely strained by more recent results[2,3], and our data show that it is no longer tenable. The alternative we have proposed requires conditions expected to be satisfied quite naturally in rich clusters: large galaxy speeds and a high intergalactic gas density. Our interpretation of the radio data is consistent with kinematic information for such clusters and with the densities required for the extended X-ray sources. It is significant that in all three clusters discussed here the Uhuru satellite has detected diffuse X-ray emission[10]; add the requirement that some of the cluster galaxies must be active radio sources of moderate power and we have a set of conditions sufficient for the phenomenon discussed to arise. Bridle and Feldman point out (personal communication) that these clusters also have very steep spectrum radio components which are probably extended sources as detected in Perseus[1] and Coma[2] and may be attributed to relativistic particles diffused out of many modestly active galaxies into the intracluster gas with its associated magnetic field. If our model is correct, narrow radio trails such as the one shown in Fig. 1 preserve information about the history of their galaxy's activity, spanning several hundred million years.

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1 Ryle, M., and Windram, M. D., *Mon. Not. Roy. Astron. Soc.*, **138**, 1 (1968).
2 Willson, M. A. G., *Mon. Not. Roy. Astron. Soc.*, **151**, 1 (1970).
3 Macdonald, R. H., Kenderdine, S., and Neville, A. C., *Mon. Not. Roy. Astron. Soc.*, **138**, 259 (1968).
4 Hill, J. M., and Longair, M. S., *Mon. Not. Roy. Astron. Soc.*, **154**, 125 (1971).
5 Chincarini, G., and Rood, H. J., *Astrophys. J.*, **168**, 321 (1971).
6 De Young, D. S., and Axford, W. I., *Nature*, **216**, 129 (1967).
7 Mills, D. M., and Sturrock, P. A., *Astrophys. Lett.*, **5**, 105 (1970).
8 De Young, D. S., *Astrophys. J.*, **167**, 541 (1971).
9 Van der Laan, H., and Perola, G. C., *Astron. Astrophys.*, **3**, 468 (1969).
10 Giacconi, R., Gursky, H., Kellogg, E. M., Murray, S., Schreier, E., and Tananbaum, H., *Astrophys. J.* (in the press).

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