THE ASTRONOMICAL JOURNAL VOLUME 86, NUMBER 8 AUGUST 1981

HIGH-RESOLUTION RADIO OBSERVATIONS OF THE X-RAY GALAXY NGC 3862 (3C 264) IN ABELL 1367

A. H. BRIDLE [a)]
National Radio Astronomy Observatory [b)] VLA Program, P.O. Box O, Socorro, New Mexico 87801
and Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131

J. P. VALLÉE [c)]
Department of Physics, Queen's University, Kingston, Ontario K7L 3N6, Canada
Received 2 March 1981; revised 11 May 1981

ABSTRACT

The radio source 3C 264, identified with the x-ray-emitting elliptical galaxy NGC 3862 in the rich cluster Abell 1367, has been mapped with resolutions from 2 to 8 arcsec at 1465 MHz using 14 antennas of the VLA. The new data delineate three main structural components: a small-diameter core in the galactic nucleus, a jet-like feature about 900 pc long emanating from the core, and an amorphous emission plateau about 11×6 kpc in radius around, but not centered on, the nucleus. The plateau occupies a region near the intersection of two large-scale radio trails extending from NGC 3862 and covers much of the optical extent of the galaxy on the Palomar Sky Atlas. The unusual amorphous plateau of emission can be interpreted as a rare class of diffusion-dominated structure formed by particles escaping from the moving active nucleus of NGC 3862. It might also however be a rapidly broadening "wide trail" source observed almost along the line of its inner structure.

I. INTRODUCTION

The extended radio source 3C 264 (= 1142+198) is identified with the bright ($V_{26} = 12.74$, Sandage 1972) E0 galaxy NGC 3862 in an outlying but dense part (richness = 2) of the cluster of galaxies Abell 1367. The cluster has been classified as Bautz-Morgan type II–III by Leir and van den Bergh (1977), and NGC 3862 is ~$0^{m}_{.}7$ fainter than its brightest member, which is NGC 3842. The overall angular size of 3C 264 increases with decreasing radio frequency (Macdonald *et al.* 1968; Northover 1976), implying that there are significant spectral index gradients across the source, and the radio structure (Fig. 1 from Högbom and Carlsson 1974) is elongated, with the galaxy at its southwestern end. Spectral gradients and symmetric placement of the optical identification are a characteristic signature of the "head-tail" radio galaxies, which are also commonly associated with the fainter members of rich clusters of galaxies. Three lines of evidence suggested to us, however, that NGC 3862 might not be a straightforward example of this type of cluster radio source.

First, the highest-resolution maps of 3C 264 in the literature, those with 12″×34″ resolution at 11 cm and 6″.5×19″ resolution at 6 cm by Northover (1976), showed emission within 1′ of NGC 3862 to both the northeast and the northwest of the galaxy, whereas the large-scale asymmetric structure lies entirely to the northeast (Fig. 1). The poor north-south resolution, and consequent declination compression of Northover's maps, left open the possibility that 3C 264 might have a "wide-angle" tail structure near NGC 3862 that was swept back into a narrower tail configuration towards the northeast.

Second, optical spectroscopy of NGC 3862 and of other galaxies in Abell 1367 left doubt whether NGC 3862 has a radial velocity significantly different from the cluster mean. Tifft and Tarenghi (1975) derived a mean heliocentric velocity of 6450 ± 130 km s^{-1} for 43 probable cluster members, while Dickens and Moss (1976) favored a mean velocity of 6610 ± 110 km s^{-1} based on 34 probable members (including one high-velocity galaxy near the cluster center). The heliocentric velocity of NGC 3862 itself has been given as 6240 km s^{-1} by Schmidt (1965), and 6592 km s^{-1} by Dickens and Moss (whose data taken by themselves imply that NGC 3862 has a rather low peculiar radial velocity). Unless the space velocity of NGC 3862 is mainly in the plane of the sky, it is unlikely that it has a very high (> 1000 km s^{-1}) peculiar velocity within Abell 1367, as the velocity dispersion of the cluster is only ~700 km s^{-1} (Dickens and Moss 1976). It may, therefore, be difficult to construct ram pressure models of its swept-back structure unless (a) the radio-emitting plasma is ejected

---

[a)]On leave from Queen's University at Kingston, Ontario K7L 3N6, Canada.

[b)]Operated by Associated Universities, Inc., under contract with the National Science Foundation.

[c)]Present address: Herzberg Institute of Astrophysics, 100 Sussex Drive, Ottawa, Ontario K1A 0R6, Canada.

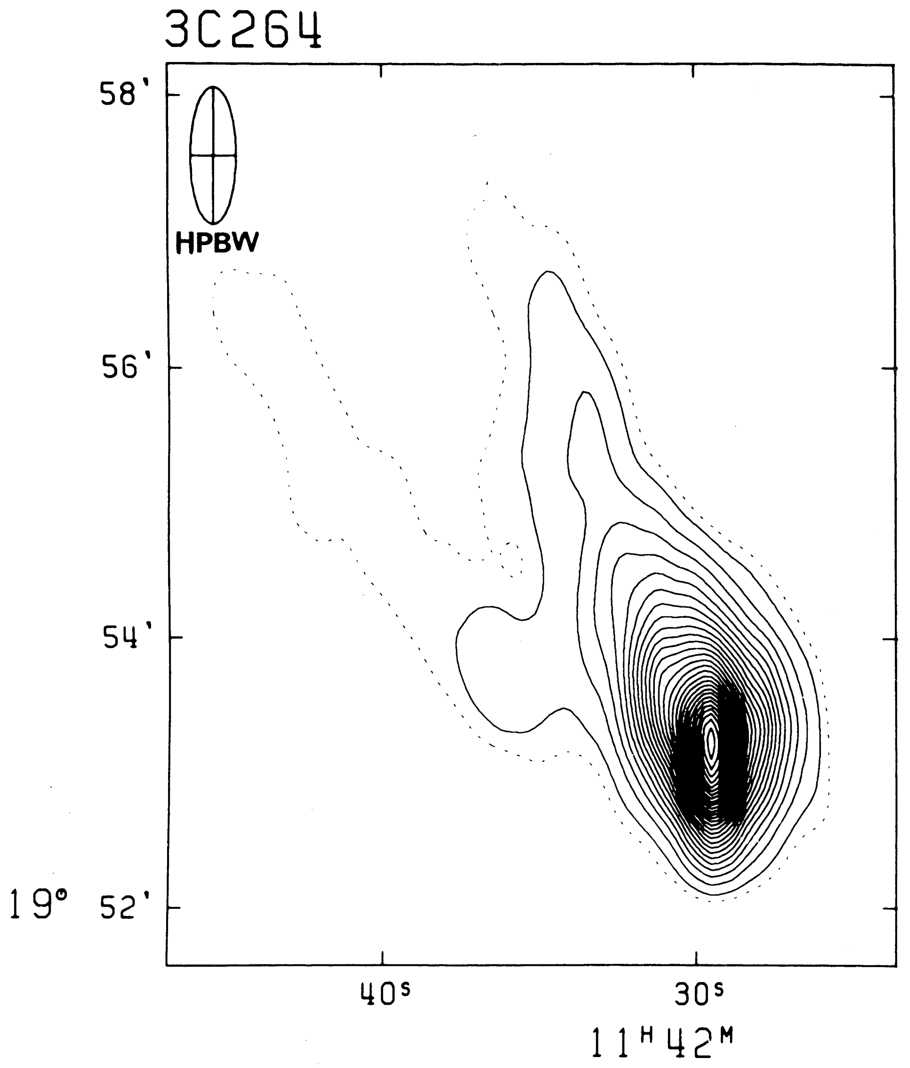

FIG. 1. WSRT 20-cm map of 3C 264 at 68″×23″ resolution, showing asymmetric large-scale structure and bifurcation of the extended trails. From Högbom and Carlsson (1974), reproduced by permission of the authors and of the editors of *Astronomy and Astrophysics.* The contour interval is 50 mJy/beam area.

from NGC 3862 at low velocity, or (b) the cluster contains a particularly dense high-temperature intracluster medium.

Third, the extended x-ray source in the direction of Abell 1367 has been mapped with the *Einstein* Observatory's IPC telescope (Jones *et al.* 1979), showing that the x-ray emission is clumped around individual cluster galaxies, among them NGC 3862, which is the strongest localized source in the cluster. The *Einstein* HRI observations (Elvis *et al.* 1981) show that the x-ray source at NGC 3862 is $<2''$ in extent and place a 3σ upper limit of $(1.9 \pm 0.5)\times 10^{34}$ W on the luminosity of any excess diffuse emission within 1′ of the nucleus of NGC 3862. There is also evidence (Elvis 1981, personal communication) from these HRI observations that the general high-temperature intracluster medium around NGC 3862 is *not* unusually dense ($n_e \lesssim 800\ \mathrm{m}^{-3}$).

These data raise the possibility that NGC 3862 is an active but slow-moving member of a cluster whose high-temperature gaseous component is not unusually dense. Its asymmetric radio structure and spectral index gradients might therefore arise by processes differing significantly from the canonical "head-tail" mechanism. We therefore observed it at 1465 MHz with the partially completed VLA (Thompson *et al.* 1980) to obtain sensitive maps of its radio structure with better north-south resolution than could be obtained at its declination with east-west arrays such as those at Cambridge or Westerbork. Section II of this paper presents the new VLA maps. Section III discusses the observed radio features of the source and Sec. IV discusses their physical interpretation.

II. THE OBSERVATIONS

The observations were made at 1465 MHz with 14 VLA antennas on 6 December 1979. Table I lists the main parameters of the observing session. All pairs of antennas were correlated, giving 91 baselines in the (u,v) plane ranging from a minimum of 87 m to a maximum of 24 km. The amplitude and phase responses of the antennas were calibrated by reference to the nearby unresolved source 1155+251, and the flux density scale was

TABLE I. Parameters of the VLA observations.

Field center (1950.0 coordinates)	$11^h42^m29\overset{s}{.}8$, $+19°53'20\overset{''}{.}0$
Date of observations	6 December 1979
Frequency, wavelength	1465 MHz, 20.5 cm
Average system temperature	60 K
Bandwidth	50 MHz
Calibration source position	$11^h55^m51\overset{s}{.}6$, $+25°06'59\overset{''}{.}9$
Scan length (source, calibrator)	12 min, 3 min
Hour angle coverage	-5^h40^m to $+6^h15^m$

VLA configuration (antenna positions)

SE arm (m) − 80.00, 44.84, 147.33, 1946.01, 3188.09, 10472.77[a]
SW arm (m) 484.00, 1589.91, 7659.46, 13643.90, 17157.20[a]
N arm (m) 54.89,[a] 266.40, 436.41

[a]Antenna at this position had only one circular polarization available.

normalized to that of Baars *et al.* (1977) by observing the source 3C 286 (= 1328+307), whose 20-cm flux density on that scale is 14.4 Jy. Nine 3-min observations of 3C 286 on either side of its transit were used to calibrate the instrumental polarization response. We assumed that 3C 286 was linearly polarized at p.a. 33° when making this calibration.

Maps of the Stokes parameters *I*, *Q*, and *U* were produced from the calibrated visibility data by the usual Fourier methods. Three antennas (see Table I) provided only one of the two circular polarizations during these observations, so their outputs were not used in the *Q* and *U* maps. The effects of sidelobe responses in the maps were reduced by application of a CLEAN algorithm (Högbom 1974; Clark 1980).

a) Map at ~8-arcsec Resolution

Figure 2 shows a CLEAN map of the total intensity (Stokes *I*) distribution over about 4′ near NGC 3862 at a resolution of $7\overset{''}{.}2 \times 8\overset{''}{.}8$ (major axis in p.a. 90°). The optical positions of the centers of NGC 3862 and IC 2955 measured by Jenkins *et al.* (1977) are marked on the map with crosses. These are the only galaxies brighter than $m_v = 18^m$ in the field shown, and IC 2955 ($m_v \sim 14^m$) is often presumed to be a companion of NGC 3862 (e.g., Nilson 1973; Northover 1976). In deriving linear scales from this and other radio maps, we assume that Abell 1367 has a mean redshift of $\langle z \rangle = 0.0215$ relative to the Local Group, and write the Hubble parameter as $H_0 = 100h$ km s^{-1} Mpc^{-1}. The luminosity distance of Abell 1367 is then 64.8/*h* Mpc.

At the resolution of Fig. 2, most of the emission detected by Northover (1976) appears to occupy an amorphous plateau whose diameter is about 1′ (18/*h* kpc). This emission plateau is centered about 15″ (4.5/*h* kpc) north of the center of NGC 3862, but is contained within the diffuse envelope of the galaxy as defined by Nilson (1973) from inspection of the E print of the Palomar Sky Atlas. This emission plateau is embedded in fainter and more diffuse radio emission extending away from it principally towards the northeast, along the axis of elongation of 3C 264 in lower-resolution maps (e.g., Fig. 1) made at 20 cm with the Westerbork telescope by Högbom and Carlsson (1974) and by Gavazzi and Perola (1981). These lower-resolution data show that there are two large-scale streams of radio emission (widths of order 1′) extending away from NGC 3862 in p.a. ~25° and p.a. ~65° which intersect in the plateau feature shown in Fig. 2. These streams are defined only by the lowest contours in Fig. 1 but are confirmed by the more sensitive WSRT maps made by Gavazzi and Perola (1981).

b) Map at ~3-arcsec Resolution

Figure 3 shows a CLEAN map of the total intensity distribution over about 2′ near the center of NGC 3862 at a resolution of $2\overset{''}{.}7 \times 4\overset{''}{.}0$ (major axis in p.a. 145°). At this resolution the brightest feature of the map is an unresolved core component that is partly blended with a feature extending ~3″ (900/*h* pc) from it along p.a. ~20°. The brightness of this feature decreases rapidly with increasing distance from the unresolved core, and it merges with the diffuse emission plateau, which contains no other comparably bright *small-diameter* features. Apart from the second-brightest peak on the map (which corresponds to an important secondary peak in the lower-resolution map shown in Fig. 2), the fluctuations in the plateau emission are close to the level at which artifacts might be produced by the action of the CLEAN algorithm on emission that is much broader than the synthesized HPBW, and which is also only a few times the peak fluctuations on the final map. We therefore believe the plateau emission to be an essentially smooth distribution of intensity at this resolution, apart from the major features referred to explicitly above.

It is clear that there is low-level emission for about 20″ (6/*h* kpc) in all directions around the bright radio core. It is only on scales broader than about 20″ that 3C 264 develops the northeast-trending asymmetry shown by the Westerbork data. Apart from the ~3″ feature extending from the core in p.a. ~20° there is no *clear*

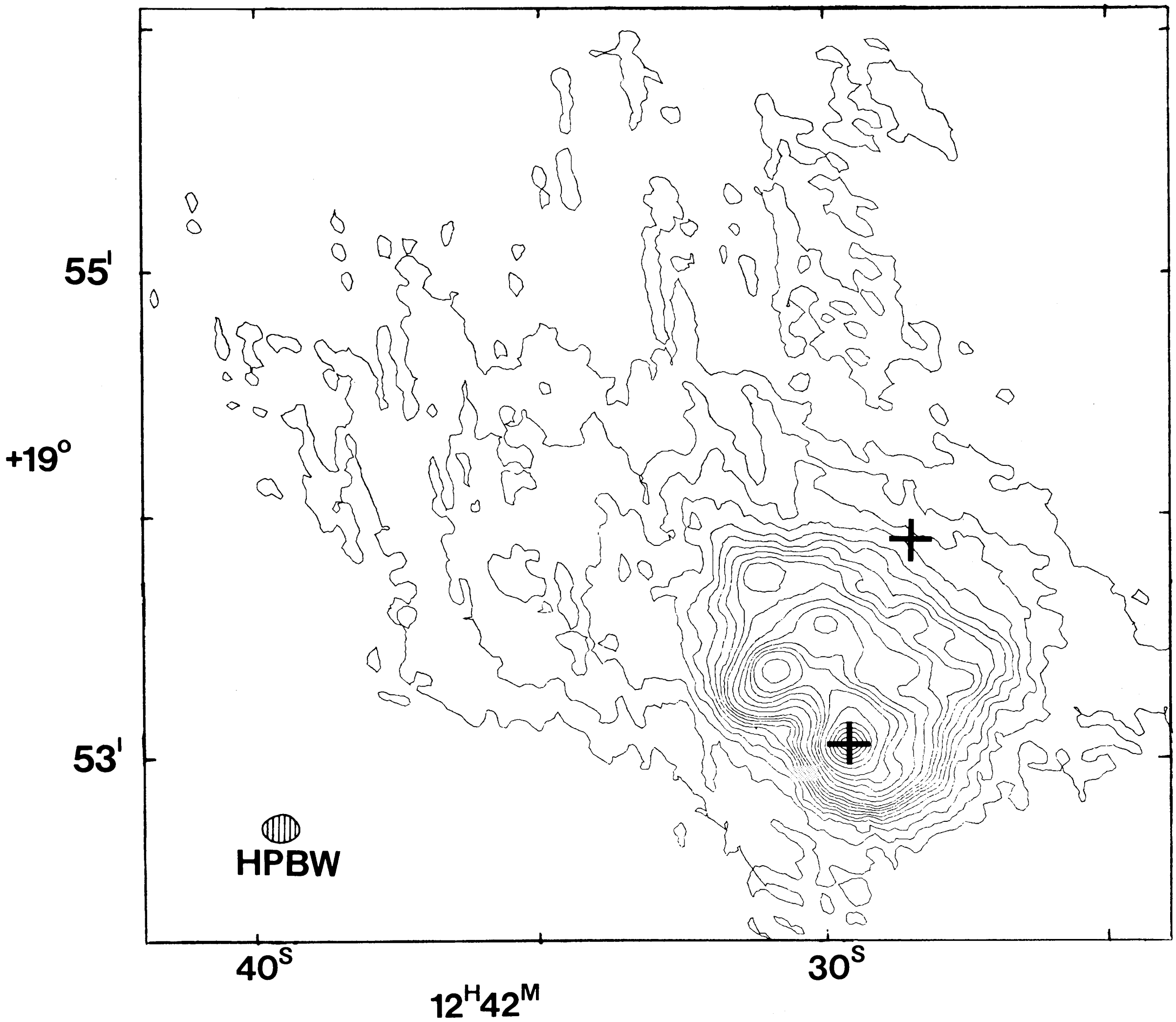

FIG. 2. VLA 1465-MHz CLEANed map of 3C 264 at $7''.2 \times 8''.8$ resolution (major axis in p.a. 90°). Contours are drawn from 4.3 to 43 mJy/beam area in steps of 4.3-mJy/beam area, from 43 to 86 mJy/beam area in steps of 8.6-mJy/beam area, and from 86 to 193 mJy/beam area in steps of 21.4-mJy/beam area. A 400-mJy unresolved source has been subtracted from the map at the position given in Table II. Crosses mark the positions of the centers of NGC 3862 (lower) and IC 2955 (upper). The scale of the map is approximately 300/h pc per arcsecond ($H_0 = 100h$ km s^{-1} Mpc^{-1}).

sign of jets of radio emission leaving the core, similar to those in most unambiguous head-tail galaxies that have been mapped with this sensitivity and resolution at the VLA [e.g., NGC 1265 (Owen *et al.* 1978), 1638+537 = 4C 53.37 (Burns and Owen 1980), IC 708 (Vallée, Bridle, and Wilson 1981), and 3C 129 (Rudnick and Burns 1981)]. If 3C 264 is indeed a "head-tail" galaxy, then it is one with a most unusual morphology around the active nucleus of its parent galaxy (at least in projection).

We now discuss the main radio features of the source in greater detail.

III. PARAMETERS OF THE RADIO COMPONENTS

a) The Nuclear Region of NGC 3862

Table II lists the positions, angular sizes, and flux densities of emission attributed to the nuclear region of NGC 3862 by various observers. The 1465-MHz parameters were derived from a map at $\sim 2''$ resolution made with no tapering of the VLA visibility data. We conclude that NGC 3862 contains an unresolved core radio source whose angular size is $< 0''.1$ (30/h pc), and whose flux density is within errors of 0.25 Jy at all frequencies between 1465 and 8085 MHz. The position of the core is $11^h42^m29^s.57 \pm 0^s.02, 19°53'02''.6 \pm 0''.2$ (epoch 1950.0 coordinates). This agrees with both published optical positions for the center of the galaxy to within their errors, and probably marks the position of the active nucleus of the galaxy. The $\sim 8''$ offset between the optical centroid and a position of the radio core derived by Bentley *et al.* (1975) must indeed be due to phase errors in their data, as they suggested. The "1.5-GHz

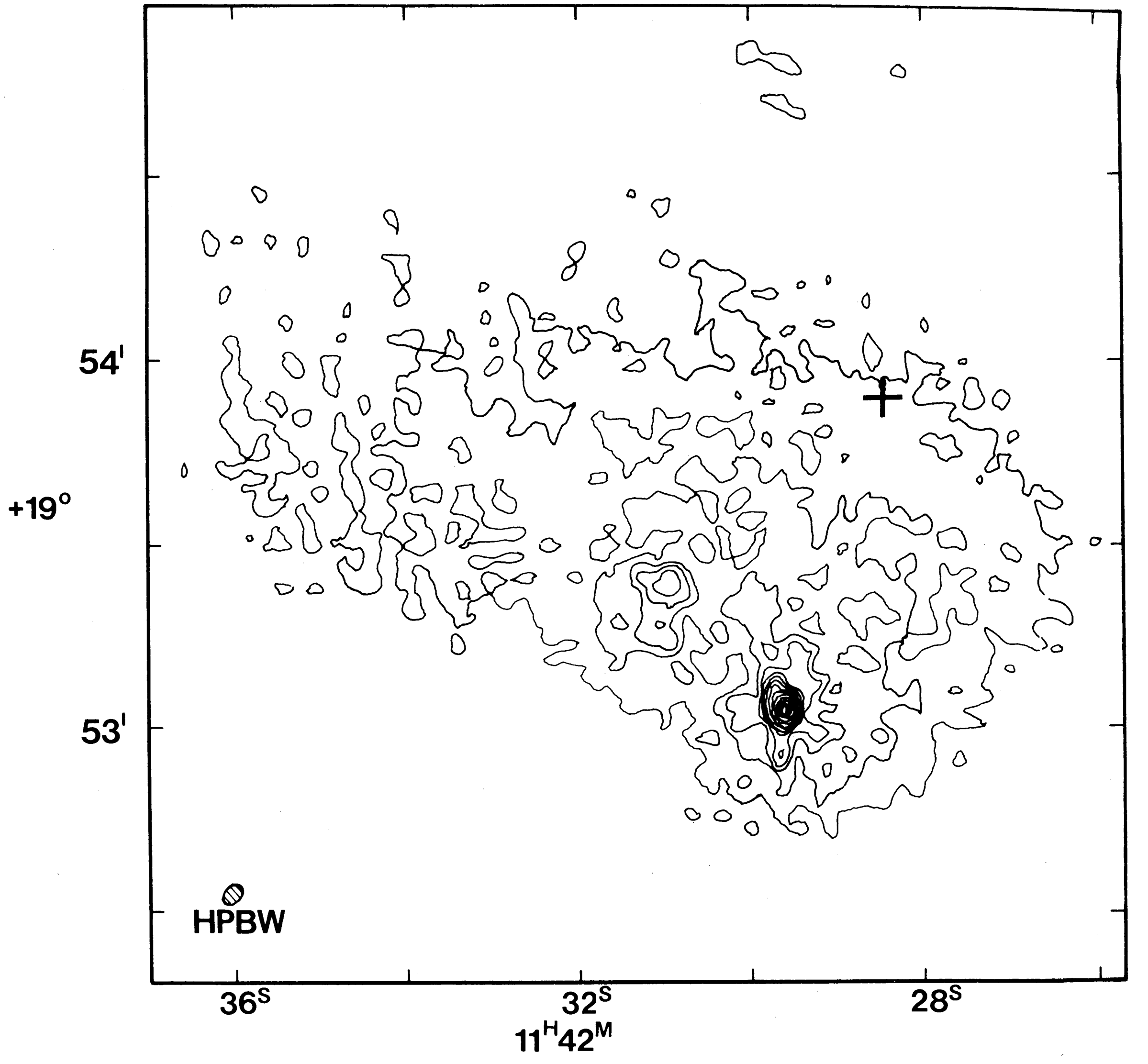

FIG. 3. VLA 1465-MHz CLEANed map of 3C 264 at 2."7 × 4."0 resolution (major axis in p.a. 145°). Contours are drawn from 4.5 to 17.8 mJy/beam area in steps of 4.5-mJy/beam area, from 17.8 to 32.1 mJy/beam area in steps of 7.1-mJy/beam area, from 32.1 to 53.5 mJy/beam area in steps of 10.7-mJy/beam area, and from 71.3 to 321 mJy/beam area in steps of 35.7-mJy/beam area. The cross marks the position of the center of IC 2955.

cutoff" in the spectrum attributed to the compact core by Northover (1976, his Fig. 3) is evidently an artifact resulting from his inclusion of emission from the ~3" feature in the flux density at 5000 MHz, but not at 1666 MHz.

The ~3" (900/h pc) feature itself also appears from the data in Table II to have a flat radio spectrum: the data are consistent with a constant flux density of 0.15 Jy for this feature from 1465 to 5000 MHz. Our VLA maps show, however, that it is difficult to detach this feature from the surrounding emission unambiguously, especially when using different resolutions at different frequencies, so we regard the flux densities attributed by different observers to this scale of emission as requiring confirmation. The feature appears unresolved transverse to its length (minor diameter < 1"), and its linear scale is similar to those of bright features at the bases of several large-scale radio jets in radio galaxies that have been mapped at the VLA, e.g., NGC 315 (Bridle *et al.* 1979) and 3C 31 (Fomalont *et al.* 1980). It is therefore possible that this feature is the brightest part of a jet, issuing from the nucleus of NGC 3862 in p.a. ~20°. Sensitive observations of the feature at higher angular resolution are required to substantiate this possibility.

At ~3" resolution the degree of linear polarization in the unresolved core is ~3%, with the E vector in p.a. 140°. The degree of polarization rises to ~12% near the northern end of the 3" feature, while the orientation remains about the same. This degree of polarization would not be unusual for a feature at the base of a radio

TABLE II. Radio emission near the nucleus of NGC 3862.

Frequency (GHz)	Angular scale	Flux density (Jy)	Reference
1.465	$<0''.5$	0.25 ± 0.05	This paper
1.465	$\sim 3''$ in p.a. 20°	0.14 ± 0.05	This paper
1.666	$\sim 0''.3$	0.24 ± 0.07	Bentley *et al.* (1975)
2.695	$<0''.1$	0.258 ± 0.011	Bridle and Fomalont (1978)
2.695	$\sim 2''$	~ 0.15	Bridle and Fomalont (1978)
5.0	$\lesssim 3.3''$ in p.a. 19°	0.40 ± 0.05	Northover (1976)
8.085	$<0''.1$	0.220 ± 0.030	Bridle and Fomalont (1978)
Positions of radio peaks and optical/x-ray centroids			
1.465 GHz	$11^h42^m29^s.56 \pm 0^s.015$	$19°53'02''.5 \pm 0''.2$	This paper
2.695 GHz, 8.085 GHz	$11^h42^m29^s.57 \pm 0^s.03$	$19°53'02''.6 \pm 0''.3$	Bridle and Fomalont (1978)
5.0 GHz	$11^h42^m29^s.58 \pm 0^s.02$	$19°53'02''.7 \pm 0''.4$	Northover (1976)
NGC 3862	$11^h42^m29^s.64 \pm 0^s.07$	$19°53'02''.5 \pm 1''.0$	Véron (1966)
NGC 3862	$11^h42^m29^s.56 \pm 0^s.06$	$19°53'02''.8 \pm 0''.8$	Jenkins *et al.* (1977)
0.5–3.0 keV	$11^h42^m29^s.9 \pm 0^s.7$	$19°53'07'' \pm 10''$	Elvis *et al.* (1981)

jet, but we cannot infer the direction of the magnetic field in the feature since the Faraday rotation there is unknown.

b) The Extended Emission Plateau

The plateau feature has steep intensity gradients to the south and southeast of the nucleus of NGC 3862, but relatively gentle gradients to the northwest, north, and northeast (where it merges with the large-scale bifurcated trail structure detected at Westerbork). The average intensity on the crest of the plateau is about 14 mJy/beam at the resolution of the map in Fig. 3, and the widths between the 7 mJy/beam levels are $70'' \pm 10''$ (north-south) by $40'' \pm 10''$ (east-west) at the widest points. The half-power widths (after deconvolution of the beam) of the corresponding emission in the 11- and 6-cm maps by Northover (1976) appear to us to be $60'' \pm 10''$ by $40'' \pm 10''$, and $50'' \pm 10''$ by $40'' \pm 10''$, respectively. The apparent size of the plateau emission therefore grows only very slowly, if at all, with decreasing frequency of the observations. Section IV of this paper discusses the interpretation of this result.

The integrated flux density of the plateau emission at 1465 MHz is 3.1 ± 0.6 Jy (subtracting a total of 0.4 Jy for the local contribution of the nuclear region described in Sec. II). The major uncertainty in this estimate stems from the arbitrariness of the distinction between the plateau and the inner trails; we consider the plateau to comprise all of the extended emission within the third contour level plotted on Fig. 2. Northover (1976) gives an integrated flux density of 2.6 ± 0.5 Jy for his 2695-MHz map, of which we estimate that 0.41 Jy arises from the nuclear region, based on the data in Table II; the emission from the plateau should therefore contribute 2.19 ± 0.6 Jy at 2695 MHz. Northover derived a flux density of 1.6 ± 0.3 Jy for the extended emission in his 5000-MHz map; this must virtually all come from the plateau feature. These data are consistent with a spectrum $S(\nu) \propto \nu^{-(0.55 \pm 0.2)}$ for the plateau emission between 1465 and 5000 MHz. The plateau therefore appears to have a flatter spectrum than the total emission from 3C 264 in this frequency range, which has $S(\nu) \propto \nu^{-(0.8 \pm 0.1)}$ (e.g., Roger *et al.* 1973). This implies that the extended trail structure has a spectrum that is significantly steeper than $\nu^{-0.8}$, consistent with the growth of the overall source size with decreasing frequency.

We did not detect any significant linearly polarized emission in the plateau region. The upper limits to the degree of linear polarization implied by this vary from 20% to 50% over the plateau.

c) The Extended Trails Beyond the Galaxy

As only the bases of these trails are of sufficient brightness to appear on the high-resolution VLA maps, we do not discuss them in detail here. Gavazzi and Perola (1981) have shown that at 610 MHz they can be traced for about 12′ (217/h kpc) to the northeast of the center of NGC 3862.

d) Equipartition Parameters

Table III lists parameters for the various radio components derived on the assumption that there is energy equipartition between the radiating particles, protons, and magnetic fields within the components, and that the electron energy spectra derived for the frequency range 1465–5000 MHz extend from 0.8 to 80 GeV. We give these parameters only to illustrate the approximate physical regimes to be expected for each component, as it is not clear that these assumptions should be expected to hold equally, or at all, for the various components and

TABLE III. Physical properties of components mapped at the VLA.

Property	Core	"Jet"	Plateau
Major diameter (kpc)	<0.03 [a]	0.90	18
Minor diameter (kpc)	<0.03 [a]	0.30	12
Electron energy index γ	1.0	1.0	2.1
21-cm luminosity (W Hz^{-1})	1.3×10^{23}	7.0×10^{22}	1.6×10^{24}
Luminosity (W)[b]	1.3×10^{34}	7.0×10^{33}	3.3×10^{34}
Minimum energy (J)[c]	6.9×10^{45}	1.5×10^{47}	5.5×10^{49}
Minimum energy density (J m^{-3})[c]	1.4×10^{-8}	1.1×10^{-10}	1.2×10^{-12}
Equipartition B (G)[c]	1.2×10^{-3}	1.1×10^{-4}	1.1×10^{-5}
Minimum confining nT (K m^{-3})[c]	3.6×10^{14}	2.7×10^{12}	3.0×10^{10}
Particle half-life (yr)[d]	1.1×10^{4}	4.1×10^{5}	1.3×10^{7}

[a]The diameter was set equal to this limit for equipartition calculations.
[b]Integrated from 10 MHz to 100 GHz assuming power-law spectrum.
[c]Assuming depth of component equal to its minor diameter, equal energies in protons and electrons, and uniformly filled component.
[d]Half-life for particles radiating at 5 GHz in equipartition field B.

as we have only rough estimates for the sizes and spectral properties of several of them.

IV. PHYSICAL INTERPRETATION

It is clear from the new VLA maps that, despite its large-scale asymmetry with respect to NGC 3862, the inner radio structure of 3C 264 does not have the typical "head-tail" morphology. Although the 3″ feature near the nucleus could be a feature similar to the base of a jet, and although this feature points roughly towards one of the large-scale trails detected at Westerbork, clearly defined and well separated bright jets such as are found near the nuclei of other "head-tail" galaxies are here conspicuous by their absence. In this section we consider two interpretations of the peculiar morphology of 3C 264, the first of which would make the source highly unusual in its physical characteristics, the second of which would make it a more normal structure viewed in a somewhat perverse projection.

a) Electron Transport by Diffusion

The observed size and shape of the plateau emission of 3C 264 can be fitted by a model in which relativistic electrons diffuse away from the slow-moving nucleus of NGC 3862. In such a model, the plateau would be interpreted as emission from a spreading reservoir of relativistic particles that is being left behind by a moving galaxy. The north-south elongation of this reservoir, the offset of its geometrical center from the current position of the radio core, and its distribution of intensity gradients could all be attributed to a generally southward motion of NGC 3862 relative to the mean velocity of the reservoir. The necessary velocity of NGC 3862 relative to the reservoir would be about half the mean drift velocity of the diffusing particles.

The spatial and energy distribution function $N(r,E,t)$ of particles diffusing through a large-scale homogeneous field in the presence of small-scale scattering irregularities would satisfy the equation

$$\frac{\partial N}{\partial t} - \nabla\cdot(D\nabla N) - \frac{\partial}{\partial E}(\beta N) = Q, \tag{1}$$

where $D(r,E)$ is the diffusion coefficient, $\beta(r,E)$ is the energy-loss coefficient, and $Q(r,E,t)$ is the source function. A wide range of astrophysically important solutions of this equation has been discussed by Wilson (1975), and specific applications to Mpc-scale diffusion of particles away from active galaxies in clusters have been described by Jaffe (1977), Rephaeli (1977), and Lea and Holman (1978). We therefore make only a brief discussion here.

For our purposes, it will be sufficient to bypass the term in $Q(r,t)$ arising from the motion of NGC 3862, by examining the spatial scale of the particle distribution in the direction *transverse* to the presumed motion. This scale can be measured by the transverse half-width between half-maxima of the radio plateau, which is $20'' \pm 5''$ ($6/h$ kpc) at each of 1465, 2695, and 5000 MHz (Sec. III b). We presume that the particle source is in the observed radio core, whose size ($<0\farcs1$, $30/h$ pc) is sufficiently small compared with the scale of the reservoir that we can represent the spatial part of the source function by a delta function $\delta(r)$ at the core. We also suppose that the injected energy spectrum of the relativistic electrons is a power law $E^{-\gamma}$, where γ is related to the observed radio spectral index α by $\gamma = 2\alpha + 1$ under the usual assumptions. (To match the oberved plateau spectrum with $\alpha = 0.55$ we will require $\gamma = 2.1$ here.)

We assume for simplicity that over most of the reservoir, the diffusion coefficient D and the loss coefficient β do not vary strongly with location r. This will obviously be too crude an approximation close to the core, but the sensitivity and resolution of the higher-frequency maps of 3C 264 do not justify making more sophisticated assumptions throughout the reservoir. As the particles will spend most of the transit time from the core to the edge of the plateau in environments well removed from

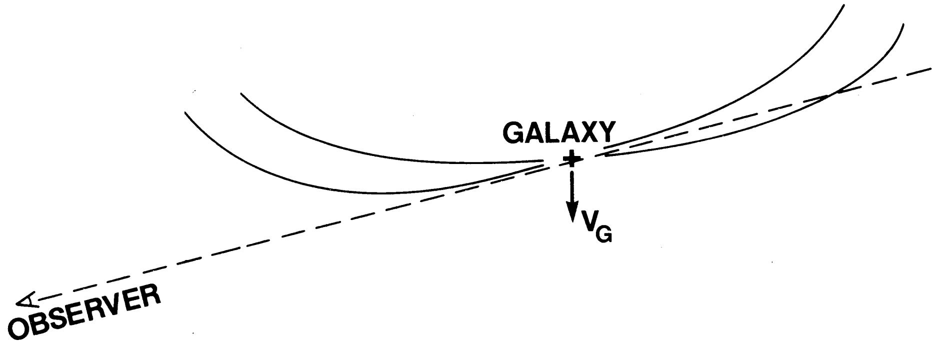

FIG. 4. Schematic diagram of possible interpretation of 3C 264 as a rapidly broadening wide-angle tail source, showing relative location of observer and source structure.

the core, this assumption is probably adequate for our present purpose. We include both the synchrotron losses of the electrons in the large-scale magnetic field B_g of the plateau and the inverse-Compton losses of the electrons on the microwave background at temperature T_γ by writing

$$\beta = bE^2, \quad b = (4\sigma_T/3m_e^2c^3)(B_g^2/8\pi + aT_\gamma^4), \qquad (2)$$

where all symbols have their conventional meanings.

The particles are assumed to diffuse in a large-scale homogeneous field of strength B_g that has small-scale scattering inhomogeneities (magnetized clouds, turbulence, etc.). As discussed by Ginzburg and Syrovatskii (1964) the diffusion coefficient D should then be virtually independent of electron energy E unless the characteristic scale of the scattering regions is much less than the electron gyroradius in those regions. Particles radiating at 1465–5000 MHz in the plateau equipartition magnetic field [1.1×10^{-5} G, Sec. III d] would have energies from 2.9 to 5.3 GeV and gyroradii in this field of only $(2.8–5.2)\times10^{-7}$pc (0.06–0.1 AU). It is very unlikely that the galactic magnetic field would have significant numbers of inhomogeneities on so small a scale, so it is reasonable to expect the diffusion coefficient D to be a constant at the energies applicable to 3C 264.

The steady-state solution to the diffusion equation for $\gamma > 1$ in these conditions is well known (e.g., Webster 1970; Lea and Holman 1978):

$$N(r,E) = \frac{Q_0E^{-\gamma}}{4\pi Dr}\exp(-bEr^2/4D) \times \frac{1}{\sqrt{\pi}}\Gamma(\gamma-1)U\left(\gamma-\frac{3}{2},\frac{1}{2},\frac{bEr^2}{4D}\right), \qquad (3)$$

where Q_0 is the amplitude of the source function and U is the confluent hypergeometric function of the second kind. This particle distribution is significantly energy dependent at a given scale r, so that the associated synchrotron emission will decrease in scale significantly with increasing frequency, unless

$$bEr^2/4D \ll 1, \qquad (4)$$

at the appropriate values of E and r. This condition amounts to the statement that the particles must be able to drift a distance r in a time that is significantly less than the characteristic time for them to lose most of their initial energy E by the synchrotron and Compton losses.

The observational uncertainties in the transverse scale of the plateau are such that we need not require *strict* energy independence of N at $r \sim 6$ kpc in this source, and we estimate that $bEr^2/4D \lesssim 0.5$ is consistent with the data. Applying this criterion for the particles radiating at 5000 MHz, where it is most severe, yields $D \gtrsim 6\times10^{25}\mathrm{m^2\,s^{-1}}$ and mean electron drift velocities $v_d \gtrsim 630$ km s^{-1}. The offset of the radio core from the centroid of the plateau emission would then require the velocity of NGC 3862 relative to the diffusing particle reservoir to be ~ 320 km s^{-1} in the plane of the sky. This seems reasonable in view of the optical velocity data described in Sec. I.

The minimum drift velocity v_d of ~ 630 km s^{-1} required by this model is consistent with the available constraints on the electron density in the circumgalactic medium near NGC 3862. One constraint arises from the *Einstein* HRI upper limit of $(1.9\pm0.5)\times10^{34}$ W to the 0.5–3-keV luminosity of any excess diffuse ($\sim 1'$) emission centered on NGC 3862 (Elvis *et al.* 1981, $H_0 = 100$ km s^{-1} Mpc^{-1}). If we assume that this limit applies to emission from an isothermal gas sphere with a King density profile with core radius $1a'$ ($18a$ kpc) and temperature $1.3T$ keV [the effective temperature of the integrated x-ray emission from Abell 1367 is 1.3 keV (Mushotzky *et al.* 1978)], then the mean electron density over the radio plateau must be $<9.1\times10^3\,T^{-1/4}a^{-3/2}\,\mathrm{m^{-3}}$. A second constraint arises from the condition that the thermal pressure of any such circumgalactic medium not overconfine the internal pressure of relativistic particles in the plateau region; with the parameters estimated for the plateau in Table III, this requires that the electron density in the circumgalactic medium be $<2.0\times10^3\,T^{-1}\,\mathrm{m^{-3}}$. A third constraint arises from the condition that the ram pressure of the circumgalactic medium on the plateau due to the motion of NGC 3862 through the medium not exceed the internal particle pressure significantly. This requires a density $\lesssim 2.7\times10^3\,V^{-2}\,\mathrm{m^{-3}}$, where the velocity of the particle reservoir relative to the circumgalactic medium is $300V$ km s^{-1}.

The reconciliation of these three constraints clearly depends on the actual values of a, T, and V in the environment of NGC 3862. If they are all near unity, however, and the density of the circumgalactic material is $\lesssim 10^3$ m^{-3}, then all of the constraints could be satisfied and the Alfvén velocity v_A in the plateau region would be $\gtrsim 760$ km s^{-1} in the equipartition magnetic field of 1.1×10^{-5} G. We therefore conclude that an electron drift velocity of $\gtrsim 630$ km s^{-1} as required by the diffusion model is quite plausible.

If the electron drift velocities are in fact close to 630 km s^{-1}, condition (4) could not be satisfied far beyond the half-power radius of the plateau, so the energy-dependent terms in (3) would take effect. It is, therefore, not surprising that the source structure beyond the plateau is known to grow in scale at the lower radio frequencies (Northover 1976). This does not mean, however, that a simple diffusion model such as that discussed here will account for the larger-scale radio trails: clearly an *anisotropic* diffusion coefficient $D(r)$ would have to be invoked to account for the slow intensity gradients and bifurcation of the trails. The required anisotropies might arise from gradients in the properties of the circumgalactic medium and/or from the configuration of any large-scale magnetic field associated with NGC 3862. In the absence of detailed information on the distribution of the total and polarized intensities over the plateau at several high radio frequencies, we can only speculate about their nature.

While diffusion models for the plateau source appear plausible, it remains unclear why similar amorphous radio structures have not been found around the active nuclei of other radio galaxies. It is particularly strange that most other sources whose large-scale structure resembles that of 3C 264 have well collimated jets emerging from their cores rather than the plateau of emission observed here. Jones *et al.* (1979) suggest that clusters whose extended x-ray emission is as clumpy as that of Abell 1367 are dynamically young, while those with smooth diffuse x-ray structures are dynamically old. It will be interesting to examine whether such clues to the dynamical age of clusters correlate with the presence or absence of well collimated jets in the cluster radio sources.

b) Electron Transport by Wide Radio Trails

Projection effects could, in principle, be invoked to explain 3C 264 as a more normal twin trail configuration with rapidly broadening trails which lie close to the line of sight near the nucleus of NGC 3862 (see Fig. 4). In such models, one might suppose the overlap between the two broad trails to form the plateau within about 20″ of the nucleus. As the trails separate in projection on the sky, they could form the asymmetric bifurcated structure which dominates Fig. 1. A distorted trail configuration of this kind would require the major component of the space velocity of NGC 3862 to lie in the plane of the sky.

The lack of clear brightness ridges around the hypothetical trail loci would require that the trails broaden rapidly with distance from the nucleus of NGC 3862, or that any narrow jets within a few kpc of the nucleus be of low luminosity. Construction of a detailed "wide-trail" model for 3C 264 on such precepts would require the introduction of a large number of *ad hoc* parameters, and we do not consider this to be worthwhile at present. A high-resolution map of the region within a few arcseconds of the core would be valuable in testing whether the 3″ feature can properly be characterized as a jet, as this interpretation would suggest.

V. DISCUSSION

The new VLA data show that 3C 264 has an unusual diffuse radio structure around the active nucleus of NGC 3862. Statistical studies of radio source structures [e.g., Mackay (1971) and the reviews by De Young (1976) and by Miley (1980)] imply that about 95% of the resolved sources in complete samples such as the Revised Third Cambridge Catalogue contain a few bright peaks of emission distributed along an elongated large-scale structure. Amorphous "haloes" or "plateaus" such as that in 3C 264 are rare. A superficially similar structure may be the 15′ diffuse envelope of 3C 84 (NGC 1275–Miley and Perola 1975; Gisler and Miley 1979; Birkinshaw 1980) but this extends well beyond the image of its galaxy on the Palomar Sky Atlas (unlike the plateau in 3C 264) and may be to some extent due to confusion with other cluster structures (Gisler and Miley 1979). We searched the literature for examples of 3C 264-like structure among weaker radio galaxies but did not find any convincing candidates. We note however that relatively few weak sources have been mapped with the combination of resolution and sensitivity now available at the VLA. It seems likely that not more than five radio sources per thousand resemble 3C 264 in their structure.

It would presently be premature to conclude whether the unusual factor in the radio appearance of 3C 264 is merely a perversity of projection in a wide-tail source or is an unusual circumgalactic environment. A search for similar structures among other radio galaxies in clusters with clumpy large-scale x-ray emission may be helpful in deciding whether the state of the hot gas around moving radio galaxies is a determinant of the degree of collimation of their radio structures.

We are indebted to Dr. R. C. Bignell and to many other colleagues at the VLA for the help and cooperation that was extended to us during the observations and their reduction. We also thank Dr. J. O. Burns and Dr. G. Gavazzi for valuable discussions, and Dr. M. Elvis for communicating the HRI results on NGC 3862 in advance of publication.

This research was financially supported by an operating grant to A.H.B. from the Natural Sciences and Engineering Research Council of Canada. A.H.B. also thanks the National Radio Astronomy Observatory and the University of New Mexico for their hospitality, while on a sabbatical leave from Queen's University at Kingston during which this work was completed.

REFERENCES

Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. (1977). Astron. Astrophys. Suppl. **61,** 99.

Bentley, M., Haves, P., Spencer, R. E., and Stannard, D. (1975). Mon. Not. R. Astron. Soc. **173,** 93P.

Birkinshaw, M. (1980). Mon. Not. R. Astron. Soc. **190,** 793.

Bridle, A. H., Davis, M. M., Fomalont, E. B., Willis, A. G., and Strom, R. G. (1979). Astrophys. J. Lett. **228,** L9.

Bridle, A. H., and Fomalont, E. B. (1978). Astron. J. **83,** 704.

Burns, J. O., and Owen, F. N. (1980). Astron. J. **85,** 204.

Clark, B. G. (1980). Astron. Astrophys. **89,** 377.

De Young, D. S. (1976). Annu. Rev. Astron. Astrophys. **14,** 447.

Dickens, R. J., and Moss, C. (1976). Mon. Not. R. Astron. Soc. **174,** 47.

Elvis, M., Schreier, E. J., Tonry, J., Davis, M., and Huchra, J. P. (1981). Astrophys. J. **246,** 20.

Fomalont, E. B., Bridle, A. H., Willis, A. G., and Perley, R. A. (1980). Astrophys. J. **237,** 418.

Gavazzi, G., and Perola, G. C. (1981). In preparation.

Ginzburg, V. L., and Syrovatskii, S. I. (1964). *The Origin of Cosmic Rays* (Pergamon, London).

Gisler, G. R., and Miley, G. K. (1979). Astron. Astrophys. **76,** 109.

Högbom, J. A. (1974). Astron. Astrophys. Suppl. **15,** 417.

Högbom, J. A., and Carlsson, I. (1974). Astron. Astrophys. **34,** 341.

Jaffe, W. J. (1977). Astrophys. J. **212,** 1.

Jenkins, C. J., Pooley, G. G., and Riley, J. M. (1977). Mem. R. Astron. Soc. **84,** 61.

Jones, C., Mandel, E., Schwarz, J., Forman, W., Murray, S., and Harnden, F. (1979). Astrophys. J. Lett. **234,** L21.

Lea, S. M., and Holman, G. D. (1978). Astrophys. J. **222,** 29.

Leir, A. S., and van den Bergh, S. (1977). Astrophys. J. Suppl. **34,** 381.

Macdonald, G. H., Kenderdine, S., and Neville, A. C. (1968). Mon. Not. R. Astron. Soc. **138,** 259.

Mackay, C. D. (1971). Mon. Not. R. Astron. Soc. **154,** 209.

Miley, G. K. (1980). Annu. Rev. Astron. Astrophys. **18,** 165.

Miley, G. K., and Perola, G. C. (1975). Astron. Astrophys. **45,** 223.

Mushotsky, R. F., Serlemitsos, P. J., Smith, B. W., Boldt, E. A., and Holt, S. S. (1978). Astrophys. J. **225,** 21.

Nilson, P. (1973). *Uppsala General Catalogue of Galaxies* (Uppsala, Sweden).

Northover, K. J. (1976). Mon. Not. R. Astron. Soc. **177,** 307.

Owen, F. N., Burns, J. O., and Rudnick, L. (1978). Astrophys. J. Lett. **226,** L119.

Rephaeli, Y. (1977). Astrophys. J. **212,** 608.

Roger, R. S., Bridle, A. H., and Costain, C. H. (1973). Astron. J. **78,** 1030.

Rudnick, L., and Burns, J. O. (1981). Astrophys. J. Lett. **246,** L69.

Sandage, A. (1972). Astrophys. J. **178,** 25.

Schmidt, M. (1965). Astrophys. J. **141,** 1.

Thompson, A. R., Clark, B. G., Wade, C. M., and Napier, P. J. (1980). Astrophys. J. Suppl. **44,** 151.

Tifft, W., and Tarenghi, M. (1975). Astrophys. J. Lett. **198,** L7.

Vallée, J. P., Bridle, A. H., and Wilson, A. S. (1981). Astrophys. J. (in press).

Véron, P. (1966). Astrophys. J. **144,** 861.

Webster, A. S. (1970). Astrophys. Lett. **5,** 189.

Wilson, A. S. (1975). Astron. Astrophys. **43,** 1.