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DEPOLARIZATION SILHOUETTES AND THE FILAMENTARY STRUCTURE IN THE RADIO SOURCE FORNAX A

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ABSTRACT

The giant radio source, Fornax A, was imaged with the VLA at 1.5 GHz with a resolution of 14″, corresponding to 2.2 kpc. It is identified with the 9th mag cD galaxy, NGC 1316, in a poor cluster. Within the radio lobes are several depolarized regions, one of which is the *silhouette* of the foreground spiral galaxy, NGC 1310, in the same group. The other depolarization regions are *not* associated with visible objects. If they are also produced by intervening material in the cluster, they would contain the mass of a typical galaxy. The lobes have unprecedented filamentary structure which is polarized and well organized; the origin of the filaments is unknown. The galaxy has an extended envelope whose edge corresponds with the inner boundary of the radio lobes.

Subject headings: dark matter — galaxies: intergalactic medium — radio sources: extended — radio sources: galaxies

I. INTRODUCTION

The radio source, Fornax A, is one of the brightest and nearest of the strong radio galaxies. Mills (1954) substantiated its identification with the peculiar $m_v = 8.8$ elliptical galaxy, NGC 1316, and Wade (1961) established its radio morphology as double with a lobe separation of 33′. A detailed optical study of the galaxy and its environs (Schweizer 1980, 1981) uncovered numerous indications of the infall of material. Further radio observations with arcminute resolution revealed that the emission in the lobes appeared circular in shape, edge-brightened, and strongly polarized, but with no hot spot—the source structure was often called *relaxed* (Cameron 1971; Gardner and Whiteoak 1971; Ekers *et al.* 1983). This interpretation was reinforced by arcsecond resolution images which detected only a faint core and a short "S-shaped" jet (Geldzahler and Fomalont 1984). What was lacking was a high-sensitivity, moderate resolution ($\sim 15''$) radio image which could resolve but not overresolve the emission in the lobes.

Observations, which were initiated at the VLA in 1985, have provided such an image. The purpose of this *Letter* is to display the morphology of the radio emission from Fornax A and to discuss two unique features of the radio source: the depolarization silhouettes and the unprecedented filamentary structure in the lobes.

II. THE RADIO AND OPTICAL IMAGES

The radio photographs of the total intensity and linearly polarized intensity distributions at 1.5 GHz with 14″ resolution, corresponding to a linear resolution of 2.2 kpc,[2] are given in Figure 1 (Plate L4). Details of the observations, image formation, and image enhancement will be given elsewhere. Fornax A contains the archetypical parts of a strong extragalactic radio galaxy: a component coincident with the nucleus of NGC 1316; radio jets protruding from each side of the core; two large, extended radio lobes; and a bridge between the two lobes.

A photograph with 14″ resolution of the optical field near NGC 1316, a cD galaxy in a poor group, is shown in Figure 2 (Plate L5). This group is 2°.5 west of the center of the Fornax I cluster. The outer parts of the envelope of NGC 1316 cover the companion Sc galaxy NGC 1317 which lies 6′ to the north. A diagram of the optical features in the NGC 1316/17 system (Schweizer 1980) has been superposed on a gray-scale image of the radio emission between the two lobes in Figure 3 (Plate L6).

Figure 4 is a gray-scale representation of the degree of polarization of the emission of Fornax A. The features are labeled as an aid to the following description of the source and the ensuing discussion, but refer back to Figures 1–3 in order to view the features with more clarity.

III. A DESCRIPTION OF FORNAX A

a) The Radio Core, Jet, and Emission near the Galaxy

The radio emission from the nuclear region of NGC 1316 is dominated by a bright component with a peak flux density of 120 mJy and an integrated intensity of 240 mJy. Faint emission extends about 30″ from this component toward each of the lobes. With higher resolution observations (Geldzahler and Fomalont 1984), all of this central emission is contained in a twin jet which is most intense near the nucleus and extends about 6 kpc toward each lobe. *No* opaque core has been detected to a level of 0.15 mJy at 15 GHz. Fornax A belongs to

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[2] A distance of 32.7 Mpc, using a recession velocity of 1635 km s^{-1} and $H_0 = 50$ km s^{-1} Mpc^{-1}, will be assumed (Schweizer 1980).

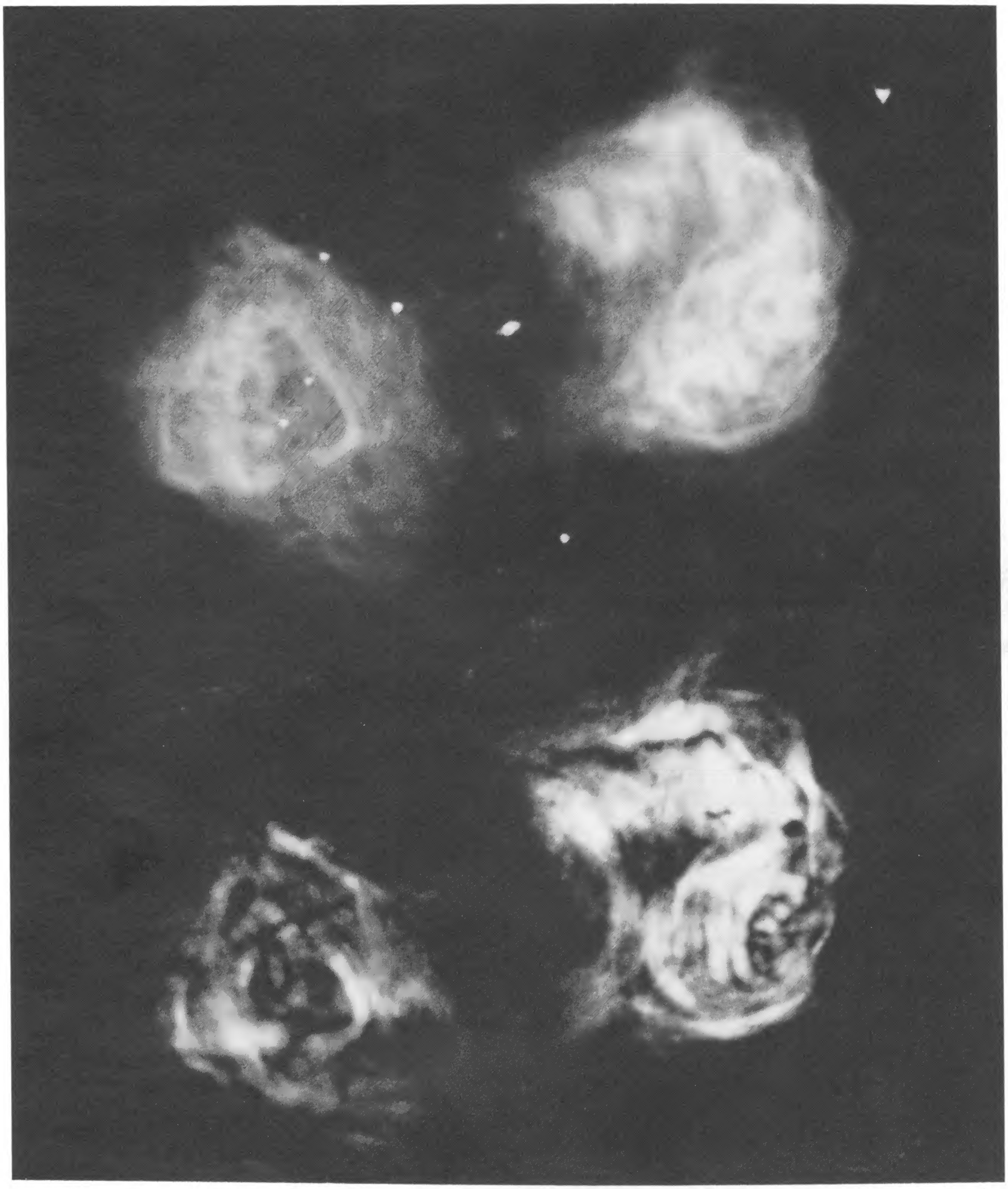

FIG. 1.—Radio photograph of the total intensity and linearly polarized intensity of Fornax A at 1.51 GHz. The resolution is 14″, and the field of view is 60′ × 40′. (*Top*) The total intensity. The maximum intensity is 120 mJy beam^{-1} at the core, and the faintest features are about 1.0 mJy beam^{-1}. The rms noise in the center of each lobe is 0.15 mJy beam^{-1}. The core is slightly extended, and the lobes contain a wealth of detail. Other point sources are unrelated background sources, and the goat-head shape of the bright source, upper right, is caused by an instrumental artifact which occurs only at the edge of the image. (*Bottom*) The linearly polarized intensity. The maximum intensity in the western lobe is 40 mJy beam^{-1}, and the faintest features are about 0.5 mJy beam^{-1}. The rms noise at the center of each lobe is 0.09 mJy beam^{-1}. The overall shape of the polarized emission is similar to that of the total intensity. However, there are several regions of low polarization of various shapes which are not associated with total intensity features.

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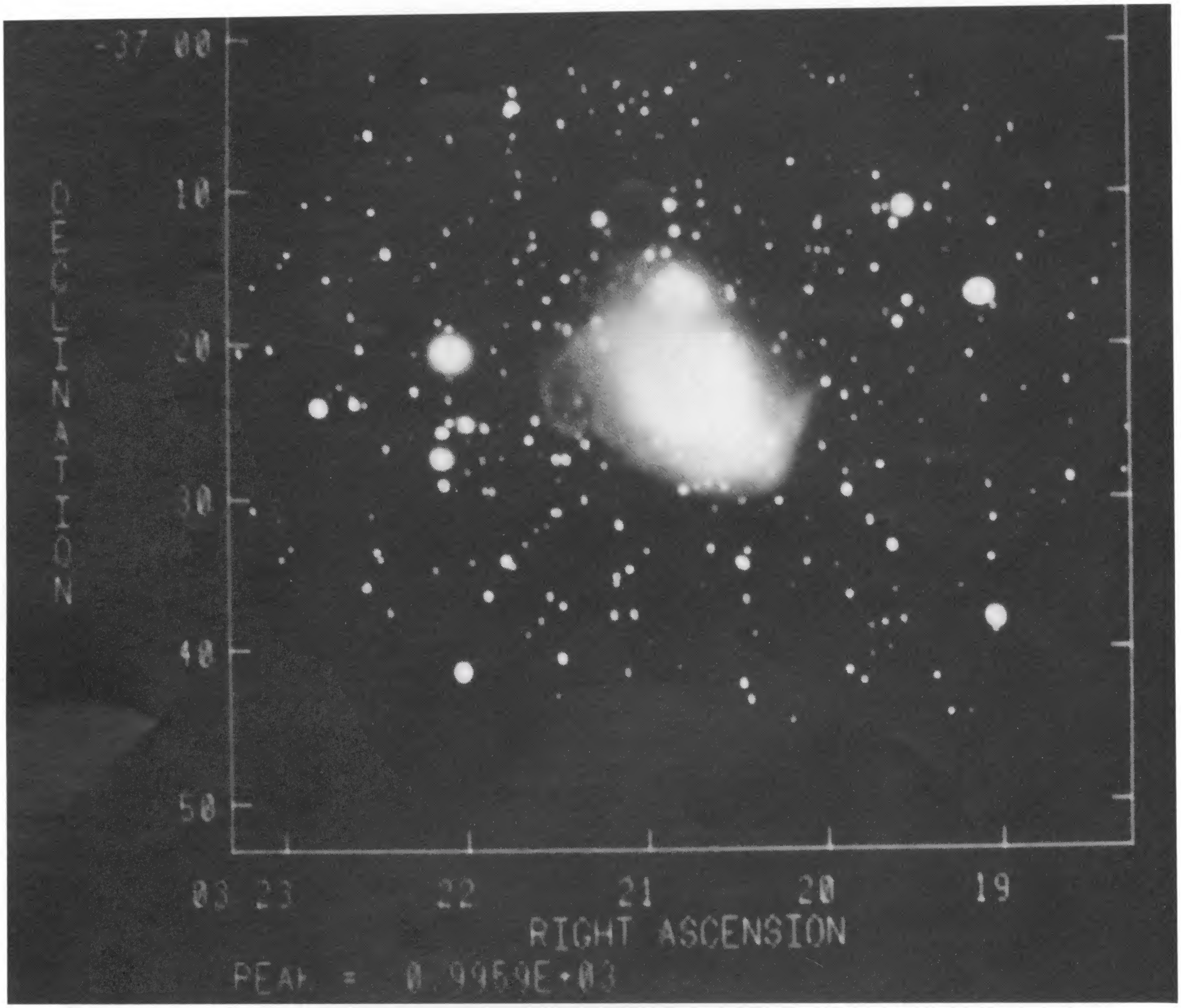

FIG. 2.—The optical field around NGC 1316/17. A high-contrast photograph (from Fig. 8 of Schweizer 1980) has been smoothed to 14″ resolution. The photograph was made from a 105 minute exposure on the CTIO 4 m telescope with IIIa-J + GG385 plates. The loop to the east of NGC 1316 is prominent, and the spur emanating from the southwest of the galaxy extends into a low-intensity region of the western lobe. The spiral galaxy NGC 1310 in the same group is 20′ west.

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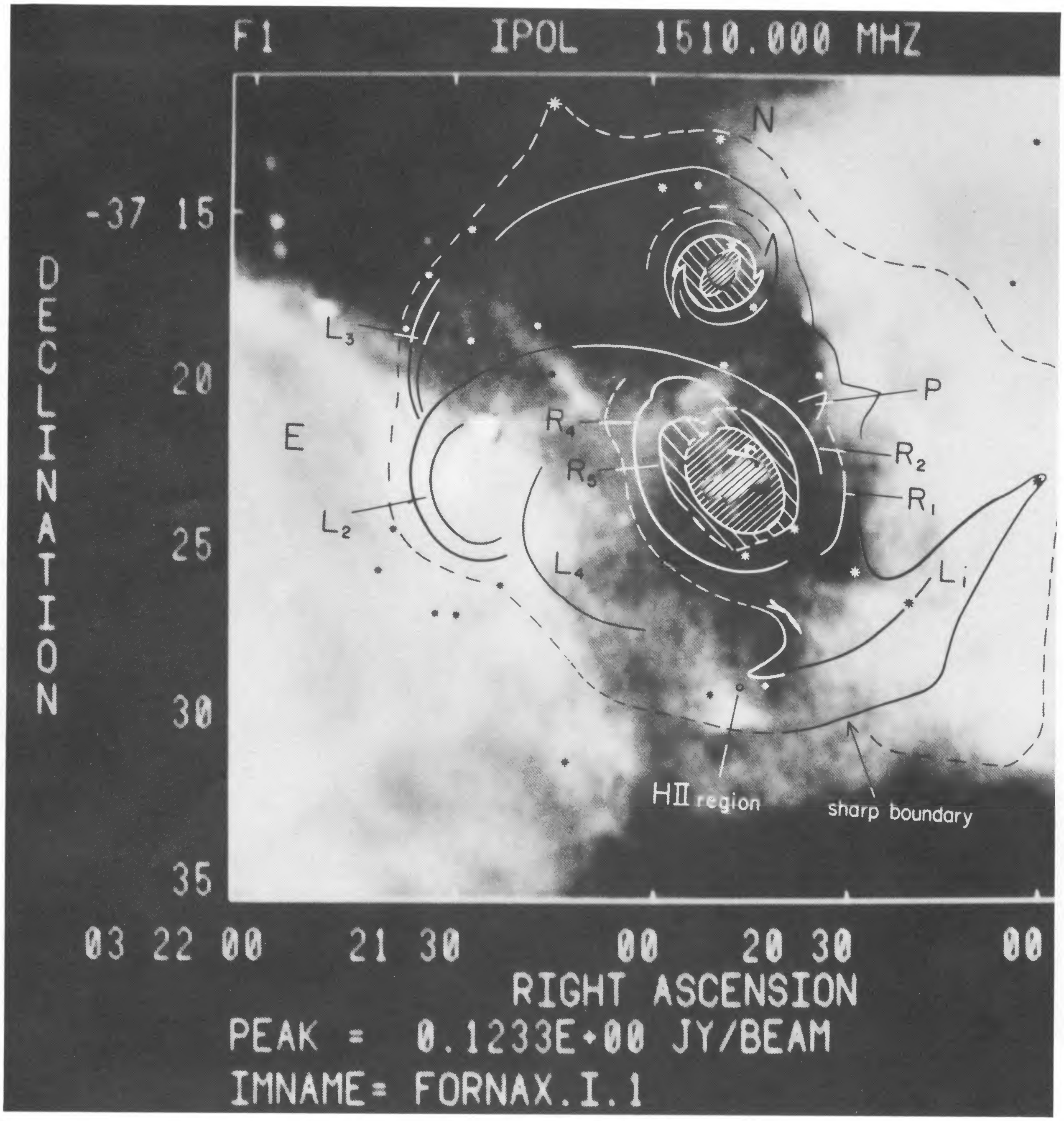

FIG. 3.—The optical features of NGC 1316 superposed on the radio emission. The optical features of NGC 1316 (Fig. 2, Schweizer 1980) are superposed on a gray scale image of the radio emission with contrast 0.3 mJy (black) to 10 mJy (white). Both NGC 1316 and NGC 1317 contain radio emission near their nuclei, and the envelope of the galaxy system fits snugly between the two lobes. There are several possible correlations between the radio and optical features.

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a class of radio sources which have extended, steep-spectrum cores which are small-scale jets emanating from the galactic nucleus (Bridle and Fomalont 1978).

A 40 mJy radio source 6′ north of NGC 1316, is coincident with the galaxy NGC 1317. The number of other discrete sources near Fornax A is consistent with the density of background sources (e.g., Windhorst, van Heerde, and Katgert 1984), and none are identified with a feature in Fornax A, except for several knots on filaments near the vortex in the western lobe.

The optical emission fits snugly between two radio lobes (Fig. 3). The western edge of the sharp emission boundary of the NGC 1316/17 system corresponds to the inner boundary of the most intense emission from the western lobe. The optical loop L_1 in the south may be associated with the southern part of the Fornax A bridge, and this loop extends well into the "bay" area of low emission in the western lobe. The bridge also contains a radio component which is near a giant H II region. Correlations between the boundary of the eastern lobe and optical emission are less prevalent, although the most intense emission from this lobe lies outside of the projected optical emission complex.

b) *The Filaments*

The filament system in the lobes of Fornax A is the most prominent of any radio source yet imaged. Other sources with filamentary structure—Cygnus A (Perley, Dreher, and Cowan 1984), 3C 310 (van Bruegel and Fomalont 1984), Hercules A (Dreher and Feigelson 1984)—are less impressive. The two nearby strong radio sources, Centaurus A (Burns, Feigelson, and Schreier 1983) and Virgo A (Hines, Owen, and Eilek 1989), which have high-quality VLA images, show less filamentary structure. All have VLA images with comparable or better linear resolution and with sufficient dynamic range in the lobe emission to detect filaments of the size and contrast as that in Fornax A.

The stronger filaments in both lobes reveal general patterns. The western lobe is dominated by the *vortex* (labeled "1" in Fig. 4; better viewed in Fig. 1 [*top*]), and the filaments in the southern part of this lobe have an approximate center of curvature about the vortex. These features are similar to those in the southern lobe of 3C 310 (van Breugel and Fomalont 1984). In the northern part of the lobe the emission (both unpolarized and polarized) is more uniform with few filaments.

The eastern lobe shows a wealth of filamentary structure which is highly polarized; the most unusual aspect is the embedded *triangular-shaped* feature. Although they are near the limits of sensitivity and resolution, the western and southern segments of the triangle are composed of three parallel filaments in both total and polarized intensity ("2" in Fig. 4; look at Figs. 1 [*top*] and 1 [*bottom*] carefully). The eastern part of the triangle is probably unrelated to the other sides; it is composed of several blobs. Less intense, shorter filaments in all orientations occur throughout the lobe.

c) *The Polarized Emission*

The darkest regions in Figure 4 have a fractional polarization about 40% with the maximum about 65%. There is negligible change in the degree of polarization between 1.38 and 1.64 GHz and the rotation measure (RM) variation is small across Fornax A—the extreme values are -15 and $+10$ rad m^{-2}, about that expected from the galactic contribution in this region of sky (Simard-Normandin and Kronberg 1980). The filaments have a fractional polarization which is typically 20%. Because of the low rotation measure in Fornax A (derived from the images between 1.38 and 1.64 GHz), the magnetic field

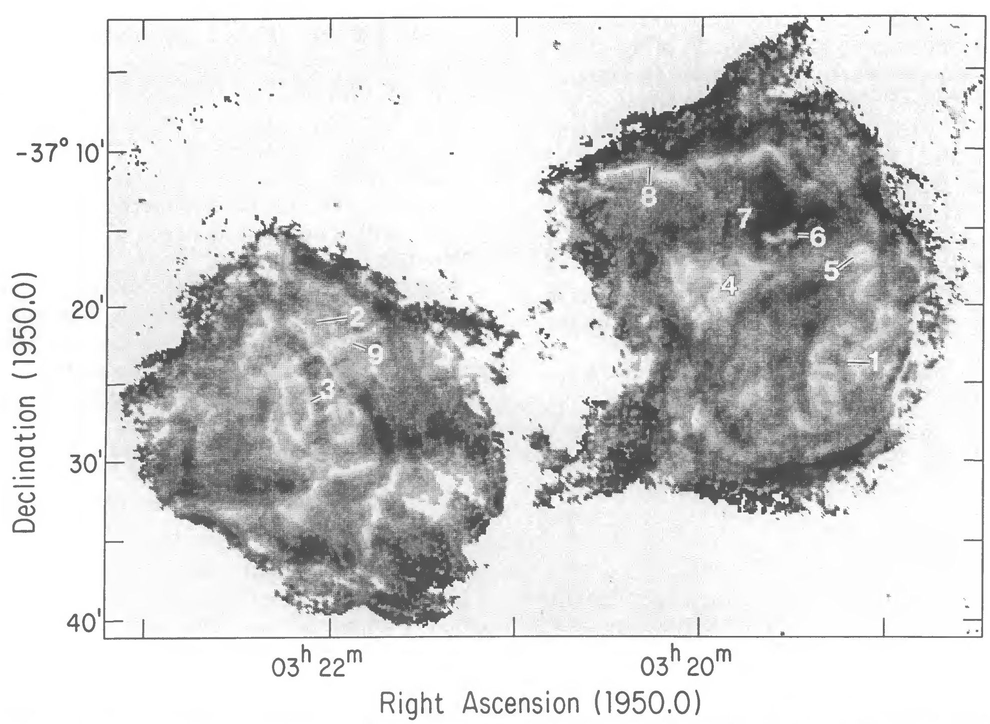

FIG. 4.—The percentage of linear polarization in Fornax A. The contrast of the image is linear between 5% (white) to 40% (black). The percentage is defined only where the total intensity is greater than 0.5 mJy beam^{-1}. Features which are discussed in the text have been labeled in this figure.

direction can be ascertained from the extrapolation of the electric vector of the polarization emission to zero wavelength. In all cases where there is sufficient signal-to-noise ratio, the magnetic field lies along the filament axis. The fractional polarization at the edge of many filaments (see "3") is less than 10%. The *bay* region in the center of the east lobe ("4") is less polarized than other parts of Fornax A.

Even with the complexity of the emission from Fornax A, there are several isolated depolarization regions which stand out as anomalies in Figure 1 (*bottom*) and Figure 4. The elliptical region in the western lobe ("5" in Fig. 4) does not correspond to any emission feature in the total intensity distribution. It is the *silhouette* of the 12.5 mag spiral galaxy, NGC 1310, which is prominent in Figure 2.

Approximately 5′ east there is an "ant-shaped" feature ("6") which is located in the middle of a highly polarized part of the lobe. There is no corresponding feature in the total intensity image, and there is no optical counterpart to a brightness limit of 27 mag (arcsec)$^{-2}$. Also noted in Figure 4 (labeled "7") are short, linear depolarization *tear-drop* features, and the depolarization strip ("8" and "9") in the eastern and western lobes, respectively. These features have little correspondence in the total intensity or optical emission.

IV. DISCUSSION

This *Letter* is limited to discussion to general aspects of the two unusual properties of Fornax A: the depolarization regions and the filamentary nature of the lobes.

a) The Depolarization Regions

The depolarization *silhouette* in the western lobe matches the optical image of the 12.5 mag, Sc galaxy NGC 1310, which is in the same group as NGC 1316 (Tully 1988). At the center of the silhouette the degree of polarization is 0.09 ± 0.03 of that in the immediate vicinity. The only plausible explanation of the depolarization is that NGC 1310 lies in front of the western lobe and material in the galaxy produces a fine-scale Faraday screen which randomizes the angle of polarization. The screen must contain sufficient material to rotate the plane of polarization of the lobe emission by at least 1 radian. At the frequency of 1.51 GHz ($\lambda = 20$ cm) this implies a rotation measure RM > 25 rad m^{-2}. The material must also be sufficiently turbulent so that a typical cell is much smaller than the resolution of 14″.

NGC 1310 is an Sc galaxy, somewhat smaller than the Milky Way, with an absolute magnitude of -20.0 and a major axis diameter of 16 kpc at the assumed distance of 32.7 Mpc. The light distribution has an axial ratio of 0.5 which implies that the plane of the galaxy is inclined about 65° from the plane of the sky (Tully 1988). If NGC 1310 contains a magneto-ionic medium similar to our Galaxy, it could produce the observed depolarization silhouette. RM variations in the plane of our Galaxy are 40 rad m^{-2} over linear scales of several hundred parsecs (Simard-Normandin and Kronberg 1980), and there are variations of 25 rad m^{-2} over size scales of a few parsecs (Simonetti and Cordes 1986; Leahy 1987). With the linear resolution of 2.2 kpc and the relatively long path length through NGC 1310, because of its large inclination, sufficiently large beam depolarization of the background polarized radio lobe should occur. However, further radio and optical observations of NGC 1310 are needed to determine the nature of the ionized medium in the galaxy.

The "antlike" depolarization feature (ALF) is similar to the depolarization silhouette of NGC 1310: It covers about the same solid angle; its minimum degree of polarization is 0.17 ± 0.02 of that of the surrounding area; and it is not associated with any feature in the total intensity emission. On the other hand, ALF is not identified with an optical feature and its shape is peculiar, although it does resemble the Large Magellanic Cloud.

ALF must also be produced by an intervening turbulent magneto-ionic medium. The alternative is that ALF emits polarized radio emission which is orthogonal to the lobe emission in the same line of sight—the depolarized shape would then be the result of the chance cancellation of polarized emission from the overlapping regions. In such a case, the total intensity emission of ALF would be superposed on the emission from the lobe, regardless of whether ALF is behind, within or in front of the lobe. No excess emission associated with ALF is observed.

Using the same arguments as that for the NGC 1316 silhouette, ALF is produced by intervening material which produces rotation measure fluctuations of ≈ 20 rad m^{-2} on an angular scale much less than 14″. If the material is in the cluster, then it would be hard to escape the conclusion that this nonluminous "ant-shaped" thing is as massive as a small galaxy. For example, if we assumed that ALF had a thickness of 10 kpc (its projected length) and a warm ionized medium (Reynolds 1988) similar to that in our own Galaxy—a uniform thermal electron density of 0.03 cm^{-3}, a magnetic field of 2 μG with a field turbulance scale of 100 pc—it would produce the appropriate Faraday screen. The emission measure for this material is 9 cm^6 pc. If the material fills the volume uniformly, the total mass in the affiliated protons would be $10^9 M_\odot$.

If ALF is local, it is unlikely to be more distant than 500 pc (the Galactic latitude of Fornax A is $-57°$). The angular scale size and amplitude constraints of the RM fluctuations can be obtained with a cloud of thickness 0.3 pc (the linear size at a distance of 500 pc), a turbulence size of 0.02 pc, a field of 10 μG, and a density of 30 cm^{-3}. Its emission measure, about 270 cm^6 pc, should produce detectable radio or optical continuum emission. A "cloud" with the above properties has not yet been detected in the Milky Way.

The "tear-drop" feature to the east of ALF (feature 7 in Fig. 4) do not correspond to a total intensity feature and may be produced by intervening material. On the other hand, the two depolarization strips may have some correlation with boundaries or filaments in the total intensity emission. The filament at the top part of the western lobe (feature 8) is associated with a faint boundary between two extended features in the total intensity emission, and the filament in the eastern lobe (feature 9) may have a faint counterpart along some of its 100 kpc length. Hence, these features could be produced by internal structure of radiating material within the lobes.

b) The Filamentary System

The formation and stability of filaments in radio lobes are not understood, and a variety of models have been proposed. For sources with strong nuclear activity and/or jets, energy flow from the core may produce the filamentary structure through shocks and turbulence (Cygnus A; Perley, Dreher, and Cowan 1984), spherical waves (Hercules A; Rudnick 1984; Mason, Morrison, and Sadun 1988), or the filling of bubbles (3C 310; van Breugel and Fomalont 1984). However, the insipid core and jet of Fornax A and the lack of a hot spot in either lobe suggest little recent energy flow to the lobes; hence, the above models are not relevant.

Radio lobes contain at least two major plasma components; a relativistic gas and a thermal gas. Unequal cooling of either component can produce thermal instabilities, clouds, or filaments (e.g., Simon and Axford 1967; Bicknell 1984). Analysis by Hines, Owen, and Eilek (1989) suggests that the time scale for the formation of filaments is longer than the radiative lifetime of the electrons—especially with the low thermal density in the lobes of Fornax A as indicated by their low rotation measure—and are unlikely to form. However, Gouveia Dal Pino and Opher (1989) suggest filaments can be formed if the energy balance between fields and particles is intermittent. Other models where transient transonic or supersonic flow occur in the lobes may produce short-lived filaments.

Filaments in radio lobes may be associated with magnetic fields and currents. The set of parallel filaments in the eastern lobe (labeled 2 in Fig. 4) is similar (although 1000 times larger) to the parallel, polarized filamentary arcs near the Galactic center (Yusef-Zadeh, Morris, and Chance 1984). Little is known about the formation of the Galactic center arcs; perhaps large-scale currents produce the filaments and their associated magnetic fields. It has been suggested (e.g., Furth, Kileen, and Rosenbluth 1963) that any diffuse current which is generated in a radio lobe would be unstable (tearing instability) and form parallel, filamentary, or helical currents. But the time scales of growth of such filaments may be longer than the electron radiative life time unless reacceleration is occurring in the filaments (Hines, Owen, and Eilek 1989).

IV. CONCLUSIONS

A depolarization silhouette in the lobe of Fornax A is produced by the foreground cluster galaxy NGC 1310. The "antlike" silhouette is probably produced in a galaxy-sized region of foreground dark material in the cluster with $>10^9$ $M_\odot$ and a significant ionized component. It is unlikely that ALF is in our Galaxy since it would be readily detectable in radio and optical continuum emission. Several other depolarization features may also be associated with cluster material.

Many questions concerning ALF are perplexing: First, how is the material ionized? Little starlight and X-rays (Forman, Jones, and Tucker 1985) are present in its vicinity. Second, what is the origin of the dark matter? Is it the remains of a galaxy which has suffered tidal distortions as it passed near or through NGC 1316, or is it remnant material in the cluster which is now forming a new galaxy? Finally, how common are such galaxy-sized regions of dark matter? Perhaps they are a significant constituent of many clusters but only the unusual properties of the radio emission of Fornax A—its large angular extent, its highly polarized lobe, its low internal and external Faraday rotation—have provided the opportunity to detect the material. On the other hand, Fornax A and the NGC 1316 system may have evolved in a peculiar manner for strong radio galaxies and counterparts to ALF may be rare.

The filamentary and fine-scale structure in the lobes of Fornax A are more prominent than for other radio sources. At the present time the theories of filament formation, confinement, and dynamics are poorly understood, and better radio data of filaments in many radio sources are needed in order to discriminate along the models. It is unknown if the filaments are long-lived or transient features with lifetimes much less than the radiating electrons.

Further observations and analyses are now in progress in order to understand the puzzling nature of Fornax A and NGC 1316 and the cluster environment.

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