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The large-scale radio structure of Fornax A

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Summary. The radio galaxy Fornax A (NGC 1316) has been mapped at 1.4 GHz with 50″ resolution using the Fleurs Synthesis Telescope. The lobes are relatively smooth but have a sharp outer boundary. The lobe to the east has a shell type structure. A bridge of emission has been found between the lobes but, unlike most other radio galaxies, this bridge is significantly displaced from the centre of NGC 1316. A scenario involving multiple galaxy collisions is discussed to try to explain the displaced bridge and the complicated dynamics of this object.

Key words: radio galaxies – galaxy collisions – NGC 1316

Table 1. Instrumental parameters

Frequency	1415 MHz
Baselines	18.3m to 786.4 m in steps of 12.2 m
Observing time	2x8 hours
Synthesized beam width	50".8 (EW) x 47".7 (NS)
Primary beam width	1°.3
First grating response	1°
Sensitivity (rms)	25 mJy/beam
Polarization	E = 90°

1. Introduction

Fornax A is one of the nearest and brightest of the radio galaxies, and is consequently well suited for detailed study at all wavelengths. Wade (1961) discovered that the source has a double-lobed radio structure with a separation of 33′. At a distance of 33 Mpc (derived from $V=1640\,\mathrm{km\,s^{-1}}$ and $H=50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) this corresponds to a linear separation of 310 kpc. The highest resolution maps of the large scale radio structure available up to now are the 80 MHz map made with the Culgoora radioheliograph (Lockhart, 1971; Morimoto and Lockhart, 1968), the 408 MHz map made with the Mills Cross with 2.′8 resolution (Cameron, 1971), and a 5 GHz map made with the Parkes 64 m telescope with 4.′0 resolution (Gardner and Whiteoak, 1971). These observations show a relatively fat double-lobed radio galaxy. Unlike the majority of radio galaxies (e.g., Mackay, 1971), Fornax A has no extension of the lobes along the major axis, but features instead a shell-like structure especially in the eastern lobe. Very much higher resolution observations have been made of the central source with the VLA at 1.4 and 5 GHz (Geldzahler and Fomalont, 1978; Fomalont and Geldzahler, 1983), but the coverage of short interferometer spacings in these observations was insufficient to map the outer lobes.

Christiansen et al. (1977) observed Fornax A with the Fleurs Synthesis Telescope (FST) with a resolution of 50″ at 1.4 GHz and detected the central source, but at the time of the observations the FST had insufficient sensitivity to detect the low brightness lobes.

The associated galaxy NGC 1316 is a peculiar elliptical galaxy with a complex distribution of stars and dust. Much more detailed information on the light distribution and the dynamics of NGC 1316 has recently been obtained by Schweizer (1980).

In this paper we present a new radio map obtained with the FST at 1.4 GHz with adequate sensitivity to show the lobes in detail.

2. Observations and data processing

The observations were made in April and May 1979. The parameters of the FST configuration at that time are given in Table 1. Attenuators were inserted to avoid saturation and overflow at the shorter spacings and the data were rescaled afterwards in the computer.

The FST observations were calibrated in the manner described by Christiansen et. al. (1977), by using a short observation of the source PKS 1934–63 to calibrate interferometer gains and phases. The FST feeds are linearly polarized and can be used only with the *E* vector at a position angle of 90°. Since the final map is normalized to give the correct total intensity for unpolarized emission, any linearly polarized component of the flux density at PA = 90° is over-emphasized by a factor of two and any component at PA = 0° is absent. The 21 cm data of Gardner et al. (1969) show that Fornax A has integrated linear polarizations of 12% at PA = 61° in the eastern lobe and 10% at PA = 101° in the western lobe. Consequently our map will be approximately

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* This work was done at C.S.I.R.O., Division of Radiophysics, Sydney, Australia, while the author was on leave from the Kapteyn Astronomical Institute

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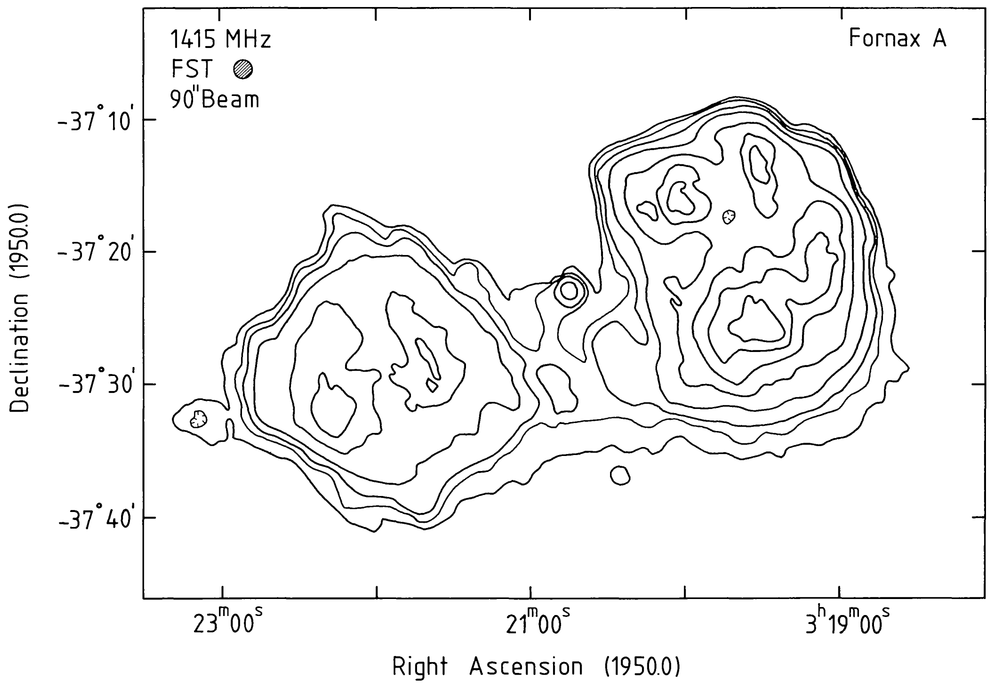

Fig. 1. Contours of the 1.4 GHz brightness distribution of Fornax A smoothed to a resolution of 90″ × 86″ ($\alpha \times \delta$). Contours are at 125, 187.5, 250, 375, 625, 875, 1125, and 1375 mJy/beam. The map is corrected for the primary beam attenuation

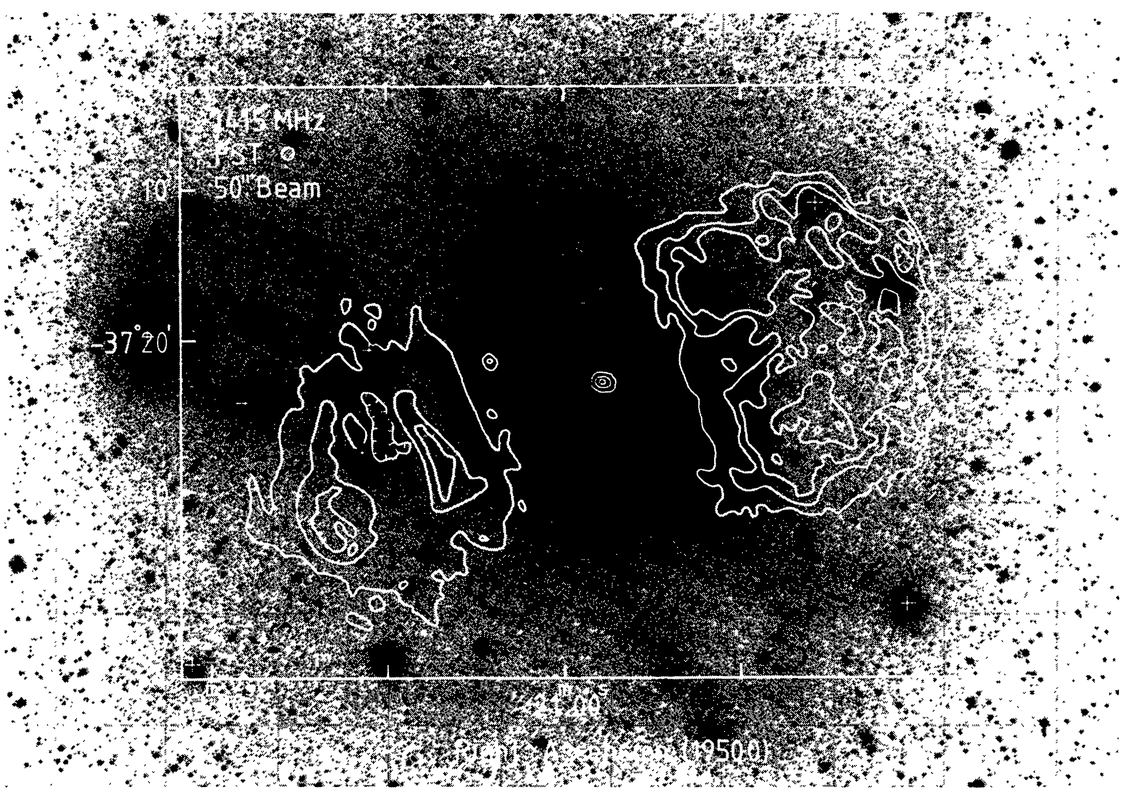

Fig. 2. Contours of the 1.4 GHz brightness distribution of Fornax A at a resolution of 51″ × 48″ ($\alpha \times \delta$). The contour levels are at 50, 100, 150, 250, 350 mJy/beam. The rms noise level is 25 mJy/beam. The optical photograph is a composite photograph from Schweizer (1980); the insert is his Fig. 5 and is printed at the same scale as the surrounding, deeper photograph

Table 2. Parameters of Fornax A

	Central source	East lobe	West lobe	Total
Flux density (Jy at 1.4 GHz)	.250	44	74	125
Power (W/Hz/ster)	2.5×10^{21}	4.6×10^{23}	7.6×10^{23}	1.3×10^{24}
Angular Size	20"	15'	17'	30'
Linear size* (kpc)	3.2	150	160	279
Luminosity (ergs/sec)	1.1×10^{39}	0.9×10^{42}	1.5×10^{42}	2.6×10^{42}
Minimum Total energy+ (ergs)	3×10^{54}	2×10^{58}	3×10^{58}	5×10^{58}
Equipartition field (μ Gauss)	6	1.5	1.7	1.6

* Adopted distance is 33 Mpc with H= 50 km/s/ Mpc

\+ Assuming equipartition and relativistic electrons only

Table 3. Discrete sources near Fornax A

No.	RA (1950)				Dec (1950)				Flux density	
	h	m	s	s	°	'	"	"	mJy	
1	03	18	38.4	± 1.0	−37	37	28	± 10	55	± 10
2	03	20	27.7	1.0	−37	37	29	10	55	15
3	03	20	41.1	1.0	−37	55	47	10	116	20
4*	03	20	46.7	0.4	−37	23	08	5	250	25
5	03	21	2.5	0.6	−37	21	39	7	108	15
6	03	21	50.2	0.6	−37	18	18	12	52	15

* Nucleus of NGC1316. Christiansen et al. (1977) give S_{21} = 150±40 mJy

correct for the eastern lobe ($2\cos 61° \cong 1$) but will over-emphasize the linearly polarized structure in the western lobe by 10%. Since the spatial distribution of the polarized intensity is unknown, there will also be an unpredictable difference between our map and the true total intensity distribution at this angular resulution.

Maps were first computed on the PDP 11/10 computer of the School of Electrical Engineering at the University of Sydney. Due to the limited size of this computer, the maps were then transferred to the PDP 11/70 of the University of Groningen. The shortest baseline in the Fleurs data is 18 m. The central part of the $u-v$ plane was filled by adding in the appropriate spatial frequencies from an E vector $=90°$ 21 cm map made using the Parkes 64 m antenna (HPBW 15′). The total flux density in our map is 125 ± 10 Jy. Maps were made at 50″ and 90″ resolution, and were cleaned (Högbom, 1974) using the "Smoothness Stabilized Clean" procedure (Cornwell, 1983), since this procedure is more suitable for extended sources.

The present maps have been corrected for the primary beam, which has an attenuation of about 20% at the edge of the maps.

3. Results

The 90″ resolution map is shown Fig. 1. Figure 2 shows the 50″ map superimposed on an optical photograph from Schweizer (1980). A shorter exposure insert shows NGC 1316 and NGC 1317 (to the north) in more detail. There is a system of faint optical arc-shaped structures and loops extending over an area similar to that of the radio lobes (see Fig. 9 of Schweizer, 1980), however there is no obvious relationship between the radio emission and any of these features. This is consistent with the suggestion (Schweizer, 1980) that they are made up of old stars.

Both the 50″ and the 90″ maps confirm the edge-brightened shell-type structure seen already in the 408 MHz map of Cameron (1971). In some regions of our maps, the outer edges of the lobes remain unresolved even at 50″ resolution. In the southern part of both lobes, however, the emission trails off more gradually. The general similarity between the 50″ and 90″ maps shows that most of the structure of the lobes is resolved (cf. the much greater brightness of the unresolved central source in the 50″ map).

A new feature seen in the present maps is the faint bridge of low-level emission (Fig. 1) which is between the two lobes, but is displaced to the south of the nucleus of the galaxy by about 8′ (80 kpc). Although bridges are common in radio galaxies this displacement is unusual because the bridges (or jets) normally connect the outer lobes to the centre of the galaxy. The new higher-sensitivity Molongolo map at 408 MHz (B. Y. Mills, private communication) shows a bridge which is offset in the same direction.

The observed radio parameters and the intrinsic properties for Fornax A are tabulated in Table 2. These are calculated making the usual assumptions of cylindrical symmetry, uniform filling, equipartition between field and particle energy and ignoring proton energy. Our position for the central source is given in Table 3 (No. 4) and agrees well with the position measured at the

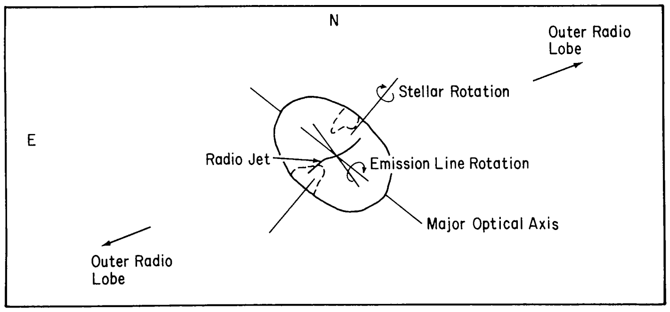

Fig. 3. A sketch showing the orientation of various features in Fornax A (cf. Table 4). The ellipse is the outline of the elliptical galaxy with the prominent dust patches indicated by dotted lines

Table 4. Axes in Fornax A

Feature	P.A. (degrees)	Angular scale	Ref
Central jet	110-148	20"	4,5
Outer lobes	∿110	16'	
Dust lane	160	1-15"	
Optical major axis	60	∿1'	1
	51	2.5-3'	1
Rotation axis (stellar)	135		2
	143		3
(emission)	37-52	54"	1

1 Schweizer (1980)
2 Jenkins and Scheuer (1980)
3 Bosma (private communication)
4 Geldzahler and Fomalont (1978)
5 Fomalont and Geldzahler (1983)

VLA by Geldzahler and Fomalont (1978). The 20″ jet extending from the central source is unresolved in our maps. Table 3 also lists various point sources found in the 50″ map and presumably belonging to the background.

4. Discussion

The ratio of component width to separation (2 : 1) is smaller than the average for radio galaxies, suggesting that the radio lobes are seen nearly end-on. It has also been suggested (Kotanyi and Ekers, 1979; Miley, 1980) that the shell type structure of the lobes may be an example of *S*-type symmetry seen in some radio galaxies. For example, 3C272.1 (Jenkins et al., 1977) or NGC 326 (Ekers et al., 1979) could look like this if seen end-on. In this respect, the new VLA observations of Fomalont and Geldzahler (1983) are of interest since they show that the central extended source has a symmetric jet-like structure with a slight bend from a position angle of 120° to 148°. The inner part of the jet is approximately aligned with the centre of the lobes while the outer part of the jet points towards the extreme edge of the emission ridges in the lobes. These position angles, together with the various optical axes, are marked in Fig. 3. If the jet and lobes are being seen nearly end-on any intrinsic variations in position angle will be amplified.

Because of their large volume and relatively low magnetic field (Table 2), the radio-emitting lobes have sufficient stored energy to radiate synchrotron emission for $\sim 4\,10^8$ yr at the present rate. If the magnetic field is as low as the equipartition value the dominate loss mechanism will be inverse Compton giving a shorter lifetime of about 10^8 yr. However for the only radio sources with reasonably well determined ages, the head-tail radio sources, ages of the tail are 3–10 times the ages indicated by radiation losses (Simon, 1979). This indicates that particle re-acceleration must be occurring as a general phenomenon. The Fornax A lobes are of similar luminosity to these radio tail sources and also show no break in the radio spectrum so it is reasonable to assume that they will also be between 10^8 and 10^9 yr old. This time span is comparable to the time scale of active history ($4\,10^8$–$2\,10^9$) suggested by the optical observations of Schweizer (1980). Therefore, features in the observed radio structure may correspond to events in the life of the galaxy.

The orientation of the different features and the offset bridge may be explained with the following scenario:

(i) The outer lobes formed almost 10^9 yr ago, before the galaxy (then a normal elliptical) had been perturbed and when it may have had a stable and well collimated beam producing a symmetric double-lobe structure at position angle 110°.

(ii) This activity was disrupted by an infalling galaxy about 10^9 yr ago (Schweizer, 1980). The bridge now seen is the remnant of the original beams, confined by the intergalactic medium, and left behind as the galaxy moves north by a projected distance of 80 kpc (at a modest 80 km s^{-1} relative to the intergalactic medium). Further support for this idea comes from the sharp northern edge and diffuse southern edges of the lobes, which also suggests a northward motion of the galaxy with respect to the surrounding medium at the time when the lobes were formed. A similar displaced bridge has been seen in 3C338 = NGC 6166 (Jaffe and Perola, 1974; Burns et al., 1983). In this case the parent galaxy has multiple nuclei and is also thought to be the result of the merging of several systems (Gallagher et al., 1980).

(iii) The more recent encounter and infalling material have triggered new activity in the nucleus leading to new radio emission from the nucleus and jet. Yet the beam formed in the present situation is not aligned with the old lobes either because the axis of the central engine has been moved, or because the jet itself is being bent by buoyant refraction in the new, non-axisymmetric atmosphere (e.g., Bridle et al., 1981). Note that the inner jet seems to align best with the stellar rotation axis, rather than with the rotation axis of the emission-line region.

This scenario is clearly speculative, but serves to illustrate the high degree of complexity of the Fornax A system.

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