AN INVESTIGATION OF THE STRONG RADIO SOURCES IN CENTAURUS, FORNAX, AND PUPPIS

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Summary

Isophotes of three strong southern radio sources have been prepared from observations at a wavelength of $3 \cdot 5$ m with a 50 min pencil-beam system. The two extragalactic sources Centaurus-A and Fornax-A are found to have extensive coronas very much larger than the size of the associated galaxies. Using optical estimates of distance these two sources are shown to have similar spatial extensions and may be physically similar systems. The third source, Puppis-A, may be the remnants of a galactic supernova of type II.

I. INTRODUCTION

The three strongest southern radio sources, Centaurus-A, Fornax-A, and Puppis-A, have been reliably identified with visible objects, the first two with the external galaxies NGC 5128 and NGC 1316 respectively (Bolton, Stanley, and Slee 1949 ; Mills 1952*b*, 1954) and the last with a peculiar galactic nebulosity (Baade and Minkowski 1954*a*). They have all been shown to have an angular extent of the order of 1° or more, and in one case (Centaurus-A) it is known that the object comprises at least two distinct emitting components (Mills 1953 ; Bolton *et al.* 1954). The major part of the published material is based on interferometer observations which had to be interpreted under various simplifying assumptions.

The aim of the present paper is to describe new observations of these sources with a high-resolution, pencil-beam system producing records which can be readily and directly interpreted. Contour diagrams of the brightness distributions across the sources have been prepared using the Sydney Mills Cross at a wavelength of $3 \cdot 5$ m. This instrument has a beamwidth between half-power response points of about 50 min of arc, and, while this is insufficient to resolve the fine structure of the sources, it is adequate to obtain a general picture of their size and shape. When used in conjunction with the interferometer data much useful information may be obtained.

The most striking feature of the observations is the extremely large dimensions of the two extragalactic sources, considerably more than that of the visible portions of the galaxies. Taking estimates of distance based on optical data it appears that the spatial extent may be similar in each example.

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II. Observations and Reductions

The radio telescope and its use have been described in detail by Mills *et al.* (1958). In the present case it is operated as a meridian transit instrument, and the aerial beam is automatically switched successively to five declinations separated by approximately 20 min of arc ; the beam is held at each declination for a period of 12 sec. The central position of the beams is set by manual adjustments to the aerial. A typical record showing the passage of the Centaurus

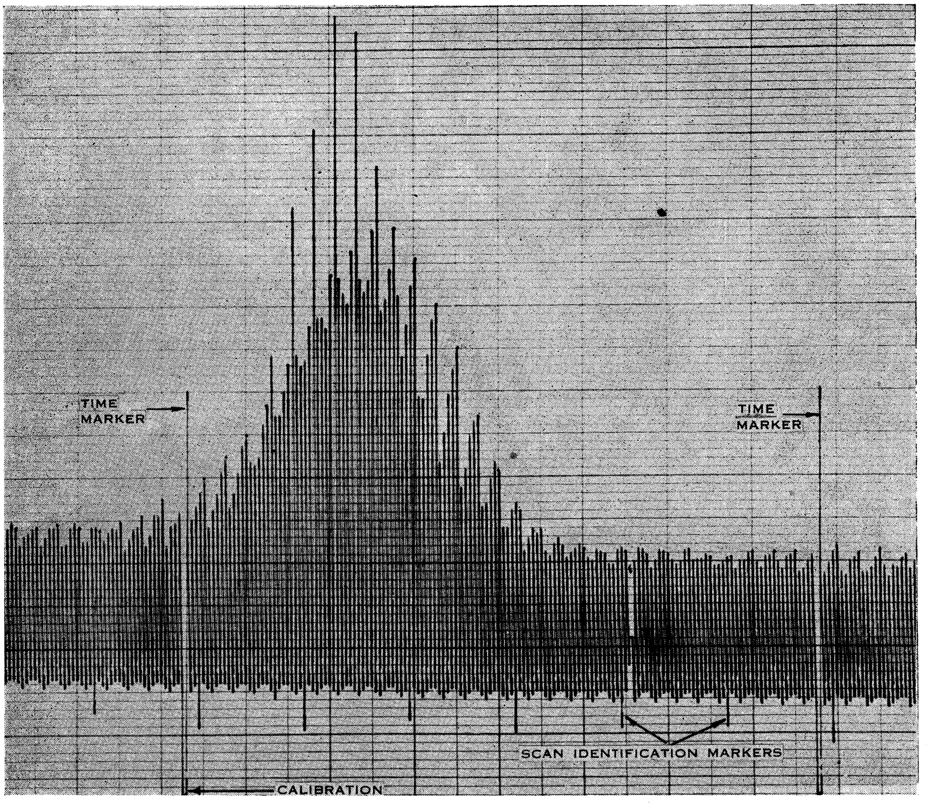

Fig. 1.—A record of a passage of Centaurus-A through the scanning aerial beam. Five separate declinations are recorded quasi-simultaneously.

source through the aerial beam is shown in Figure 1. The recorder deflection at the top of one of the lines is proportional to the average aerial temperature observed with the aerial pointed to one declination for the 12-sec period. The five declinations are scanned from south to north so that every fifth line on the chart corresponds to the same declination. The aerial temperatures* are therefore observed at points on a grid with spacings 1 min in Right Ascension

* The procedure necessary to correct for various instrumental effects is described by Mills *et al.* (1958). These corrections, which include those for beam asymmetries and collimation error, have been applied to the data quoted subsequently.

Table 1

3·5 M RADIO MEASUREMENTS AND ASSOCIATED OPTICAL DATA

Radio Source	I.A.U. No.	Position (epoch 1950)*		Flux Density* S (10^{-24} W m^{-2} (c/s)$^{-1}$)	Estimated Angular Size†		Radio Magnitude‡ m_R	Associated Optical Objects				m_R—m_P	Approx. Distance§ (kpc)
		R.A.	Dec.		Major Axis	Minor Axis		NGC No.	Position (epoch 1950) R.A.	Position (epoch 1950) Dec.	Photo. Magnitude m_P		
Centaurus-A	13S4A	$13^h\ 22^m·4±0^m·2$	—42° 41′±4′	87±13	6°	2°	1·7	5128	$13^h\ 22^m·47$	—42° 45′·6	6·5	—4·8	750
Fornax-A	03S3A	$03^h\ 20^m·6±0^m·2$	—37° 23′±3′	9·5±1·5	0·7°	≈0·5°	4·2	1316	$03^h\ 20^m·7$	—37° 25′	9·5	—5·3	5000
Puppis-A	08S4A	$08^h\ 20^m·9±0^m·3$	—42° 52′±4′	6·9±1	0·8°	0·8°	4·5	Galactic nebulosity	$08^h\ 20^m·3$	—42° 48′	—	—	0·5

* Errors shown are estimated probable errors based on uncertainties in system parameters.
† Angular size estimates for Fornax-A and Puppis-A derived on assumption of Gaussian distribution across the sources.
‡ Radio magnitude defined by $m_{R(3·5m)}=—53·4—2·5\log_{10}S_{(3·5m)}$.
§ Distance estimates for Fornax-A and Centaurus-A (de Vaucouleurs 1956) and Puppis-A (Baade and Minkowski 1954*a*).

and 20 min of arc in declination. These spacings are sufficiently small to define the distribution uniquely within the resolution limits of the aerial (Bracewell 1956).

The records include the effects of both source and background radiation. The background temperature can be removed by interpolating between regions around the source. This process was easily applied to the Fornax-A records, as the background level is practically uniform in this region, but was rather more difficult in the case of the Puppis-A source, which is superimposed on a steep galactic gradient.

The removal of the background was not performed on the Centaurus-A source because it covers such a large area that interpolation becomes very subjective; consequently it was decided to present the direct observational data.

Observations of the Fornax and Puppis regions required records at 15 declinations, involving three different manual settings of the aerial. However, the five most important sections straddling each source were obtained within periods of about 10 min. Because of the great size of the Centaurus source records at over 30 declinations were required. To minimize the effects of any calibration changes occurring in the period during which the records were obtained, the background temperatures were matched at a particular Right Ascension (viz. $13^{h}\,01^{m}$) where the temperature was nearly uniform over the declination range concerned. After smoothing the temperatures at this Right Ascension (to discriminate against the possible inclusion of small sources) and plotting against declination, the calibration changes were detected by noting if groups of five consecutive points were displaced to one side of the curve. Ten sections were corrected, one group by 10 per cent. and the others by about 5 per cent. This process merely smoothed the background level, to avoid irregularities in the final plot.

For each source an additional set of curves was constructed along hour circles (using the above east-west sections) and used to interpolate in declination. To complete these curves, use was made of the interpolation theorem of Bracewell and Roberts (1954) to compute extra points at declination positions between the east-west sections. The values so obtained are those which would result if the aerial beam was actually pointed to these positions.

Both sets of curves were used to construct contour maps for each source, following the method outlined by Mills *et al.* (1958). The procedure was straightforward for Fornax-A and Puppis-A but more complicated for Centaurus-A owing to the effects of aerial side lobes in the north-south directions in which Centaurus-A is greatly extended. These small effects were removed by a smoothing process.

III. Discussion

The results of these observations are summarized in Table 1 which sets out the radio features together with some optical data and estimates. The three sources will be discussed in turn.

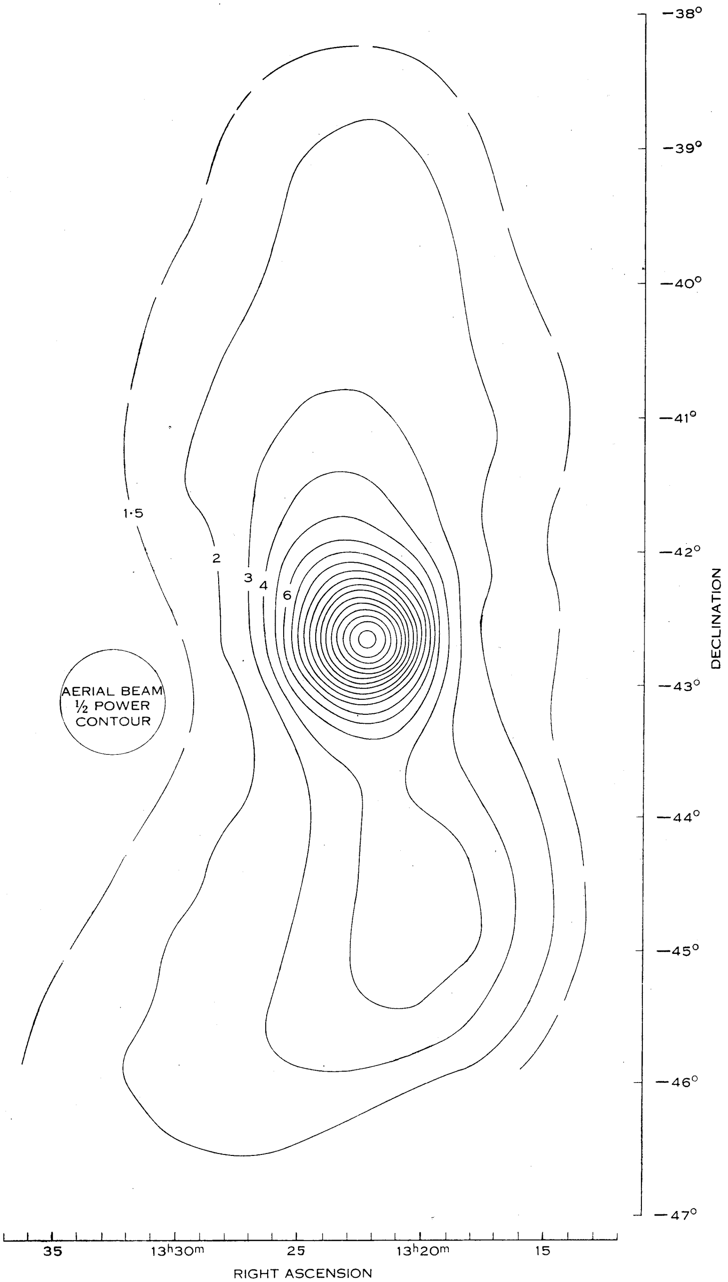

Fig. 2.—Radio isophotes of Centaurus-A at a wavelength of 3·5 m (epoch 1950), contour interval 3000 °K.

(a) *Centaurus-A*

Radio emission from this source was first detected by Bolton (1948) using a 3 m wavelength sea interferometer. He reported its angular width as less than 15 min of arc. Subsequent observations have revealed two contributions: intense radiation from a small area of about 6 by 3′ coincident with the position of the galaxy NGC 5128, and a much more extensive and less bright area surrounding the galaxy. Mills (1953) measured the brightness distribution across the source with an interferometer at a wavelength of 3 m and found about 45 per cent. of the total energy in the central concentration, with a maximum brightness temperature of about 4×10^6 °K.

A preliminary investigation to determine the main features of the radio brightness distribution was made with the present aerial in an early state of its development and the result has been compared with the optical brightness distribution (de Vaucouleurs and Sheridan 1957). The radio results were presented as contours of apparent equal brightness temperature above a smooth interpolated reference level but were uncorrected for aerial beam asymmetries and side lobes. The main result of this comparison was that a reasonable agreement existed in the east-west directions but the radio distribution was much more extensive in the north-south directions.

Figure 2 shows radio isophotes (epoch 1950) constructed from the later, more accurate, observations described above. The contour interval is 3000 °K and the galactic background has not been removed. The background distorts the outermost contours slightly, but otherwise will have little effect on the distribution. The contours show a large source, of apparent maximum temperature about 5×10^4 °K, considerably elongated in position angle about 12°. Emission is intense over an area of about 2 by 6° and is strongly concentrated in the central region with the peak at $13^{\text{h}}\,22^{\text{m}}\cdot4\pm0^{\text{m}}\cdot2$, $-42°\,41'\pm4'$. This peak corresponds closely to the " point source " at the centre which is, of course, not resolved. To determine the integrated flux density S of the source the background was first subtracted by smoothly interpolating through the base of each section and then evaluating, over the remaining contours, the expression $S=(2k/\lambda^2)\int T\mathrm{d}\Omega$. The value obtained was $S=(87\pm13)\times10^{-24}$ W m^{-2} (c/s)$^{-1}$. The uncertainty in this value (±15 per cent.) is an estimated probable error based on uncertainties in the system parameters. Approximately 25 per cent. of this flux density is contained in the central concentration.

The extended emission between declinations $-35°$ to $-46°$ has a shape bearing slight resemblance to the letter " S ". Piddington and Trent (1956) suggested a " link " between this source and the Galaxy (at a wavelength of 0·5 m) but no evidence in support of this was found in the 3·5 m results.

Extensive radio coronas are perhaps associated with most galaxies, a fact consistent with an origin in the emission of high energy electrons by the synchrotron mechanism, but the Centaurus-A source is peculiar in having such an elongated shape. Baade and Minkowski (1954*b*) consider that the interaction of two separate galaxies is involved. The distance of the system is not definitely established, but it has been estimated by de Vaucouleurs (1956) to be about

750 kpc. At this distance the linear dimensions of the extended source would be about 90 by 30 kpc. At the distance adopted by Burbidge and Burbidge (1957), 2·5 Mpc, the linear dimensions would be greater by a factor of more than 3. This seems unlikely, and their estimates of total emission from the source are probably rather too high.

(*b*) *Fornax-A*

Discovered in 1948 by Stanley and Slee, this source has since been identified by Mills (1954) with the galaxy NGC 1316. From preliminary observations with the Cross, Mills described it as an elongated object of overall size about 1° with the major axis in position angle about 160°.

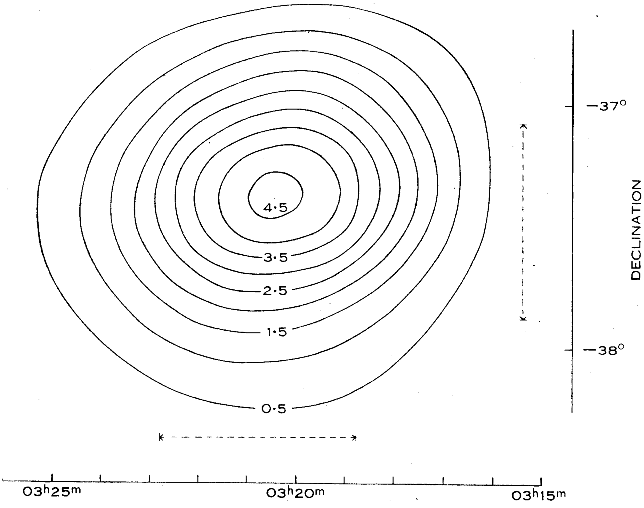

Fig. 3.—Radio isophotes of Fornax-A at a wavelength of 3·5 m (epoch 1950), contour interval 1500 °K. The dashed lines indicate the aerial beamwidth between half-power points in the directions shown.

Figure 3 shows the recently determined contours, at 3·5 m, free from background emission, the contour interval being 1500 °K. The centroid position of this emission is at $03^{h}\ 20^{m}{\cdot}6 \pm 0^{m}{\cdot}2$, $-37°\ 23' \pm 3'$ (epoch 1950), a value which agrees with Mills's determination, and is almost exactly the position of the galaxy.

By integration over the contours of Figure 3 the flux density, at a wavelength of 3·5 m, is $S = (9{\cdot}5 \pm 1{\cdot}5) \times 10^{-24}$ W m^{-2} (c/s)$^{-1}$.

This source is only barely resolved by the aerial and therefore the somewhat irregular shape of the contours can only indicate that the source itself possesses some structure. Its effective angular size* is estimated to be about 0·7 by 0·5°. The orientation of the contours appears to change with distance from the centre

* To obtain an effective angular size θ_e, a Gaussian distribution was assumed for the source and use made of the expression $\theta_e = (\theta_0^2 - \theta_b^2)^{\frac{1}{2}}$, where θ_0=angle between half-power contours of the observed distribution, θ_b=angular width of the aerial beam between half-power points.

but the overall effect suggests a position angle of about 115°. A photograph shown by Baade and Minkowski (1954*c*, p. 130) indicates the position angle of the main body of the nebula as about 45°, and reveals some absorption patches along a line whose position angle is about 135°. These figures suggest that the strong radio emission might be associated in some way with the appearance of the absorption patches, but little weight can be given to this opinion until radio observations with higher resolving power are available.

The radio emission extends over a much greater area than the galaxy. Taking the distance as 5 Mpc (de Vaucouleurs 1956) and the effective angular size as about 0·7 by 0·5° the radio corona has a linear extent of about 60 by 40 kpc. This is of a similar order of magnitude to that of Centaurus-A,

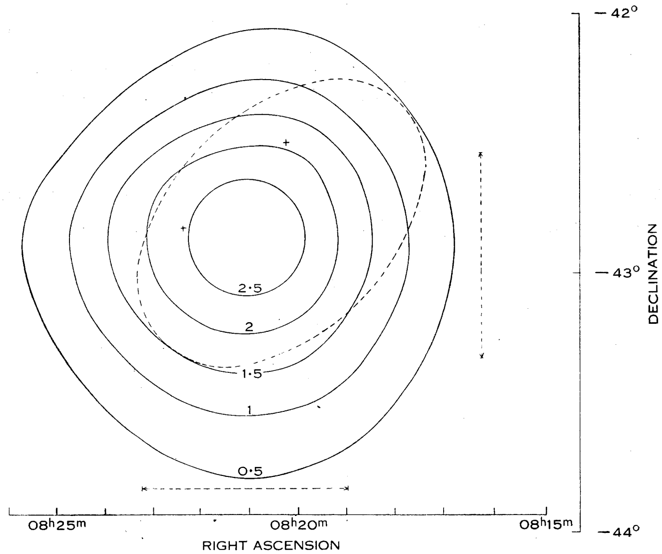

Fig. 4.—Radio isophotes of Puppis-A at a wavelength of 3·5 m (epoch 1950), contour interval 1500 °K. The dotted ellipse defines the boundary of the filamentary nebulosity associated with this source. The dashed straight lines indicate the aerial beamwidth between half-power points in the directions shown.

suggesting that the two sources might have similar physical origins. It is not yet possible to decide whether there is any similarity in the detailed distribution of the radiation in the two sources, in particular whether Fornax-A exhibits a structure combining an intense localized source and diffuse corona as suggested by Burbidge and Burbidge (1957).

(*c*) *Puppis-A*

The radio source, Puppis-A, was discovered by Stanley and Slee (1950). Using the position they quoted together with an angular size determined by Mills (1952*a*), the source was identified by Baade and Minkowski (1954*a*) with a network of gaseous filaments similar to those in Cassiopeia.

Figure 4 shows the radio isophotes, at a wavelength of 3·5 m, for this source. The background emission has been removed from these contours, which have intervals of 1500 °K. The centroid position of the source is at $08^{h}\ 20^{m}\cdot 9 \pm 0^{m}\cdot 3$, $-42°\ 52' \pm 4'$ (epoch 1950), and the integrated flux density is $(6\cdot 9 \pm 1) \times 10^{-24}\ \mathrm{W\ m^{-2}\ (c/s)^{-1}}$. The source is definitely resolved and the effective angular size is estimated to be about $0\cdot 8°$.

Included in Figure 4 is a dotted ellipse which marks the boundary of the nebulosity discovered by Baade and Minkowski (1954*a*). Its coincidence in position with the radio source is very close. Emission from the radio source extends over a slightly greater area than the optical source. Although there is some uncertainty in the shapes of the contours owing to possible errors in the removal of the galactic background, it is possible that the slight bulging of the contours on the northern and eastern edges is associated with two of the brightest parts of the nebulosity whose approximate positions are indicated by the crosses in Figure 4. The interferometer observations of Mills (1952*a*) indicate that there is no outstanding region of emission of small angular size associated with Puppis-A. Because of its similarity to Cassiopeia, Puppis-A may be a supernova of type II. The weaker radio emission from Puppis-A may indicate that it is an older supernova.

An estimate of the distance to this source using hydrogen line absorption techniques is very desirable to determine the spatial extent and total emission.

IV. Acknowledgments

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