THE RADIO EMISSION FROM CENTAURUS-A AND FORNAX-A

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Summary

Observations of the sources Centaurus-A and Fornax-A at 19·7 Mc/s, with a 1°·4 aerial beam, have been compared with observations at higher frequencies, in particular with Sheridan's 85·5 Mc/s observations. There are marked similarities between the sources, in their general appearances, linear dimensions, spectra, and powers radiated at radio frequencies.

More detailed discussion of the Centaurus-A observations strongly suggests that the extended component of this source has a spiral structure. It appears to be associated with the bright ellipsoidal part of NGC 5128, but possible association with the dark band cannot be excluded. One plausible interpretation of the data leads to an estimated age of the source of the order of 10^7 years.

I. Introduction

Although the number of radio sources now catalogued runs into thousands, only few of these can be identified, even tentatively, with optical objects, and the number reliably identified with external galaxies is even smaller. Two of this group, Centaurus-A and Fornax-A, associated with NGC 5128 and NGC 1316 respectively, are of particular interest, firstly in that the two galaxies, especially NGC 5128, are peculiar objects optically, and secondly because both sources have angular sizes which can be resolved with the present-day aerial systems of the Mills Cross type of radio telescope. It has already been shown by Sheridan (1958) that the Sydney 85·5 Mc/s Cross aerial, with its beamwidth of 0°·8, can be used effectively in the study of the brightness distributions across these two sources. Alongside the 85·5 Mc/s Cross at the Fleurs field station, near Sydney, N.S.W., is another Cross, working at a frequency of 19·7 Mc/s and with a beamwidth of 1°·4. This equipment has also been used to study Centaurus-A and Fornax-A.

The object of the present paper is first to describe the 19·7 Mc/s observations of these two sources and then to compare the results of these observations with those at other frequencies, especially Sheridan's observations at 85·5 Mc/s. Such a comparison of the available information about the two sources supports the hypothesis first advanced by de Vaucouleurs (1953) that the two associated galaxies have similar general physical characteristics. Finally, the great angular extent of the Centaurus source permits the study of its brightness distribution in some detail, and this leads to certain conclusions about the structure of the source.

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II. The 19·7 Mc/s Observations

The main features of the aerial system and the method of recording have been described previously (Shain 1958). The radio telescope operates as a transit instrument, but aerial-switching gives quasi-simultaneous recording for five declinations separated by about 33 min of arc. The central declination can be changed by manual adjustment of the aerial, and the manual settings are usually arranged so that the northernmost of the five records for one setting should correspond to the southernmost record of the neighbouring setting, but in practice, owing to refraction in the ionosphere, the position in the sky to which the aerial is pointing at any time is different from the nominal position.

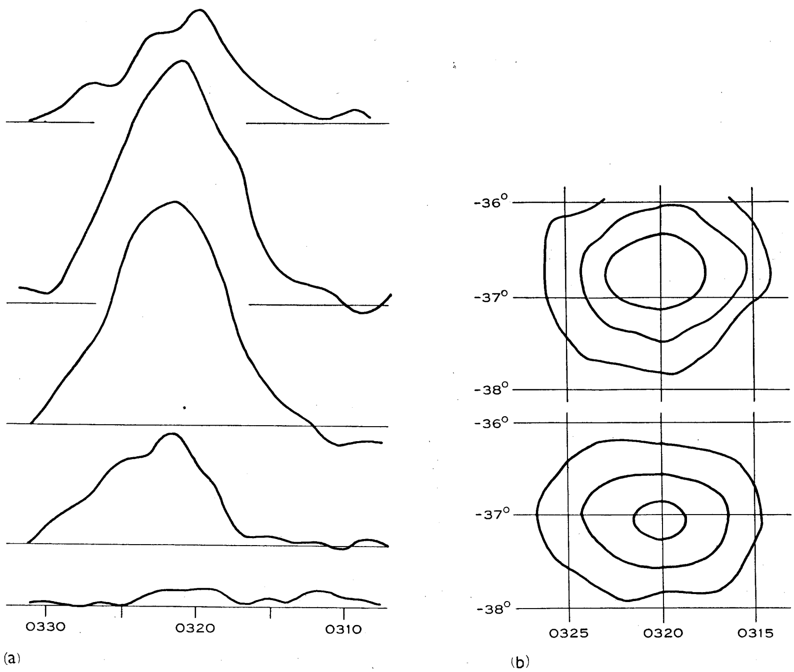

Fig. 1.—Observations of Fornax-A. (*a*) The five records at different declinations obtained on November 13, 1957. (*b*) Contour diagrams prepared from records such as those shown in (*a*). Upper diagram : November 13, 1957 (cf. (*a*)) ; lower diagram : November 7, 1957.

Both Centaurus-A and Fornax-A were observed only when they were within 10° of the zenith and all the observations were made between midnight and dawn. The *F*-region critical frequency was always less than 8 Mc/s, and, under these conditions, the expected refraction due to the curvature of the ionosphere should be small—less than about 3 min of arc (see, for example, Bailey 1948). However, the ionosphere is never simply stratified horizontally ; at any time the electron density varies with both latitude and longitude, these variations producing apparent changes in the declination and Right Ascension respectively of extra-terrestrial sources. Smith (1952) has studied the refraction in Right Ascension at 81·5 Mc/s, but it has now been found that the refraction in declination is equally important, and at 19·7 Mc/s the day-to-day variations of refraction in both coordinates may be 0°·5 or more.

An investigation of the relationship between the observed refraction and ionospheric conditions is being undertaken in this Laboratory, but so far there is insufficient information for the accurate forecasting from ionospheric sounding data of the refraction which might be expected. In any case, for the periods covered by the present observations, the ionospheric data from Australian stations was unfortunately incomplete. Because of the uncertain refraction, the records on different days were therefore made with the aerial beam pointing at directions in the sky which were not accurately known. Under these circumstances, the quasi-simultaneous recording of five separate declination scans was of very great value, making possible the empirical fitting together of the various records. As an illustration of the procedure adopted, the simpler case of the Fornax-A records will be outlined first.

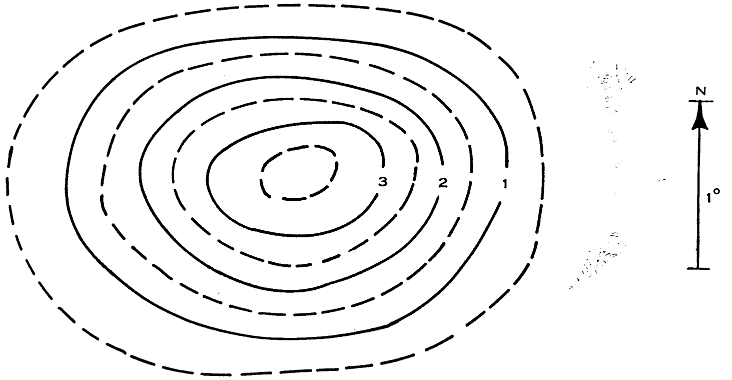

Fig. 2.—Isophotes of Fornax-A as observed at 19·7 Mc/s. The numbers on the contours give apparent brightness temperatures in units of 108,000 °K.

In observing Fornax-A, the central position of the aerial beam was set close to the known declination of the source, and it was found that the five scans covered the source almost completely; tracings from one of the records are shown in Figure 1 (*a*). It was therefore possible to draw isophotes from each day's observations, and it was found that these isophotes had generally similar shapes (scintillations sometimes caused some distortion) but their apparent positions changed from day to day, as illustrated by Figure 1 (*b*). Four records were selected which apparently were free of scintillations and of any interfering signals, and the isophotes drawn from these records were superimposed in such a way that each set fitted the others as well as possible. Average brightness temperatures were then computed at intervals of 1 min in Right Ascension and 17 min of arc in declination and from these a composite set of isophotes was constructed. This is shown in Figure 2.

A similar process was adopted in reducing the Centaurus-A observations, but in this case observations with six different central positions of the aerial beam, necessarily made on different days, were required to cover the great angular extent of the source. At least two records were taken for each beam position. Isophotes were again drawn for each day, and it was found that there was sufficient detail in them not only to match the records for one beam position, but also to match the isophotes for neighbouring beam positions with only very small

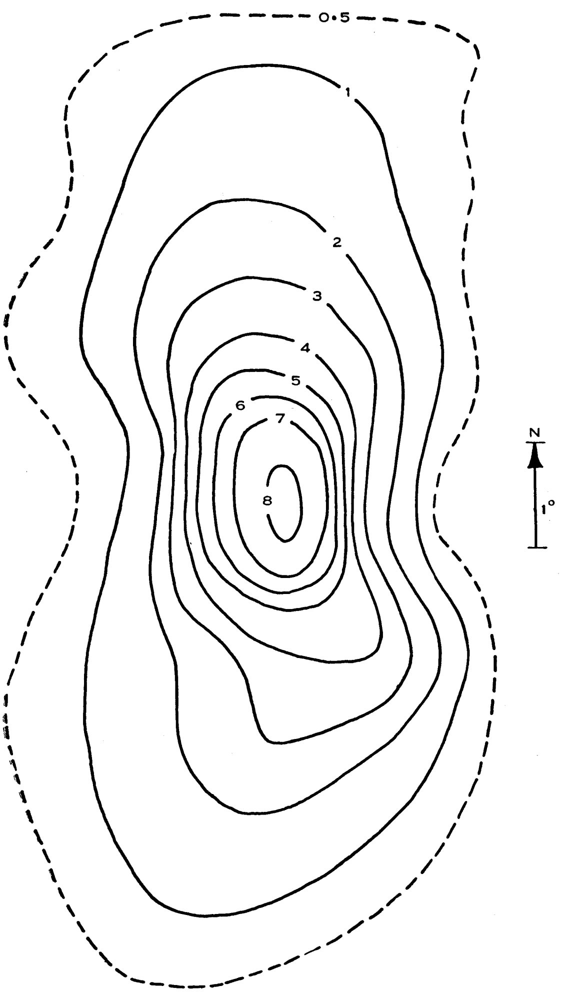

Fig. 3.—Isophotes of Centaurus-A as observed at 19·7 Mc/s. The numbers on the contours give apparent brightness temperatures in units of 100,000 °K.

uncertainty. In this way isophotes of the whole source were built up. The effects of the side lobes of the north-south aerial beam were removed in the manner described by Sheridan, and the effect of the background radiation, which changes only slowly in this region of the sky, was estimated and subtracted. The final result is shown in Figure 3, which depicts the isophotes of Centaurus-A as observed at 19·7 Mc/s.

The positions of the sources have not been indicated in Figures 2 and 3 because of the uncertain ionospheric refraction. The shapes of the 19·7 Mc/s isophotes are very similar to the shapes of the 85·5 Mc/s isophotes and it is assumed that the sources have the same positions at 19·7 Mc/s as at 85·5 Mc/s. Rough estimates of the refraction suggest that this assumption is correct. As regards intensities, relative values should be accurate to rather better than 10 per cent., but the uncertainty in the absolute scale is probably about 20 per cent.

Integration over the contours gives the following values for the flux densities of the sources:

Centaurus-A .. 280×10^{-24} W m^{-2} (c/s)$^{-1}$, of which 11 per cent. is concentrated in an unresolved central source;

Fornax-A .. 43×10^{-24} W m^{-2} (c/s)$^{-1}$.

III. Comparison of Centaurus-A and Fornax-A

(a) *Apparent Shape and Linear Dimensions*

A cursory inspection of Figure 3 shows that Centaurus-A is a very elongated source. In fact it may be objected that this extended source may be a chance superposition of a local galactic source on the " point " source which has already been identified with the dark obscuring band across the external galaxy NGC 5128. However, there are no other similar bright galactic features in this part of the sky, and the symmetry of the extended source about NGC 5128 is very strong evidence against the objection. If a rough allowance is made for the beamwidth of the aerial, the source extends for about $7\frac{1}{2}°$ in the north-south direction and about $2\frac{1}{2}°$ in the east-west direction. These dimensions are slightly larger than those observed at 85·5 Mc/s, and this is a real difference between the appearances of the source at the two frequencies, not just an effect of differing aerial resolution. The central " point " source is not resolved by either Cross.

Fornax-A is also an extended source. At 85·5 Mc/s it is only just resolved in the north-south direction, with an angular width of 0°·5 or less, but at both 85·5 and 19·7 Mc/s it is clearly resolved in the east-west direction, the angular lengths, allowing for aerial beamwidths, being about 0°·8 and 1°·1 respectively. Although it is not possible from the Cross results to say whether or not there is a strong central concentration as for Centaurus-A, Sheridan has pointed out that the complexity of the 85·5 Mc/s contours indicates some small-scale structure. It is possible that the greater angular extent at 19·7 Mc/s may be partly due to the greater contribution of an extended source to the total flux compared to that of a localized central source.

To get some idea of the linear dimensions of the two sources, it is necessary to estimate their respective distances, about which there is some uncertainty. For definiteness, we will take the estimates of de Vaucouleurs (1956), who gave the approximate distance of NGC 5128 as $7\cdot5\times10^{5}$ pc, and of NGC 1316 as 5×10^{6} pc. The distances can hardly be much larger than these since Baade and Minkowski (1954*a*) comment that, even if only at 5×10^{5} pc, NGC 5128 must be one of the most luminous spheroidal galaxies. We then find that Centaurus-A extends over an area of about 100 by 30 kpc, and that the long dimension of Fornax-A is also about 100 kpc.

(*b*) *Spectra*

(i) *Centaurus-A*.—There have been many observations of this source, extending over a wide range of frequencies, but until the results of the Cross observations became available there was no reliable means of separating the contributions to the total flux density from the central source and the extended source, which has been called a " halo ", but which is now seen to be very elongated. It was noted above that at 19·7 Mc/s 11 per cent. of the flux is received from the unresolved central source. At 85·5 Mc/s the proportion is 23 per cent. (Sheridan 1958), and it is immediately clear that the two components must have different spectra.

In the light of the present observations, it is now possible to use earlier observations to estimate the spectrum of the two components separately. The sea-interferometer observations by Stanley and Slee (1950) at 60, 100, and 160 Mc/s and some of the observations by Mills (1952) at 101 Mc/s were made with the interferometer fringes so closely spaced that only the central source would be recorded. Observations at frequencies greater than 1000 Mc/s (Piddington and Minnett 1951 ; Haddock, Mayer, and Sloanaker 1954 ; Hagen, McClain, and Hepburn 1954) have been made using aerial beams ranging from $1^\circ{\cdot}4$ to $0^\circ{\cdot}5$. These aerials would have accepted only a small fraction of the radiation from the extended source, which, in any case, is comparatively weak at high frequencies. It follows that these very high frequency observations refer only to the central source, any small part of the extended source included in the aerial beams being faint and insignificant.

At 600 Mc/s Piddington and Trent (1956) give the integrated flux density from the whole source, and at 400 Mc/s McGee, Slee, and Stanley (1955) show contours from which the total flux density can be derived. At these two frequencies the contribution of the central source has now been estimated from the spectrum of this component, and this has been subtracted from the total flux density to give the flux density of the extended source. Shain and Higgins (1954) measured the total flux density at 18·3 Mc/s but no attempt has been made to separate the two components.

Figure 4 shows plots of the observed flux densities against frequency, and also lines corresponding to a variation of the flux density S with frequency f of the form $S=kf^{-n}$, where k and n are constants. In Figure 4 (*a*) the observed total flux density is plotted and the observations are fitted for a value of $n=1{\cdot}0$. In Figure 4 (*b*) the two components are separated and the values of n are $0{\cdot}6$ for the central source and $1{\cdot}25$ for the extended source. The difference in spectra of the two components is confirmed.

(ii) *Fornax-A*.—Because of its lower flux density, this source has been studied less extensively than Centaurus-A. Apart from the Cross observations, the total flux density has been measured by Shain and Higgins (1954) at 18·3 Mc/s, by Bolton *et al.* (1954) at 100 Mc/s, by McGee, Slee, and Stanley (1955) at 400 Mc/s, and by Piddington and Trent (1956) at 600 Mc/s. The observed flux densities are plotted in Figure 4 (*c*), and, although there is some uncertainty, the value of n for Fornax-A must be close to 1.

(iii) *Ratio of Radio and Photographic Flux Densities.*—As extreme extensions of the spectra of the two sources, we may consider, for each source, the ratio of the flux density observed at a low radio frequency to the corresponding flux density observed in the photographic region of the spectrum. For this purpose we take the total flux densities observed at 85·5 Mc/s by Sheridan and the total photographic magnitudes listed by de Vaucouleurs (1956). These latter have been converted to flux densities using formulae given by Allen (1955, p. 174). We then find that the ratio of 85·5 Mc/s to photographic flux density for Centaurus-A is 1100, and for Fornax-A 1800.

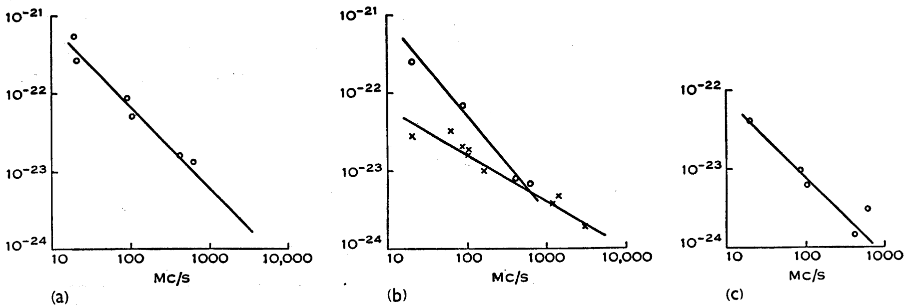

Fig. 4.—Spectra of Centaurus-A and Fornax-A. (*a*) Spectrum of the total flux density of Centaurus-A; the slope of the line is —1·0. (*b*) Spectra of the two separate components of Centaurus-A. Circles: extended source, slope —1·25; crosses: central source, slope —0·6. (*c*) Spectrum of the total flux density of Fornax-A, slope —1·0.

(*c*) *Power Radiated*

As the values of n, describing the spectral variations of the sources, have been estimated, it is now possible to estimate the total power radiated in the radio-frequency range. In the absence of any observational evidence concerning cut-off frequencies, these were arbitrarily fixed, following Burbidge and Burbidge (1957), at 10 and 3000 Mc/s. Integration of the spectra then gives directly the radio-frequency flux received at the Earth, namely, for Centaurus-A (total) $3 \cdot 9 \times 10^{-14}$ W m^{-2}, and for Fornax-A 4×10^{-15} W m^{-2}. Taking the distances adopted above, we then find that the powers radiated by the sources are:

Centaurus-A	(central source)	$1 \cdot 0 \times 10^{39}$ erg/sec
	(extended source)	$1 \cdot 7 \times 10^{39}$ erg/sec
	(total)	$2 \cdot 7 \times 10^{39}$ erg/sec
Fornax-A		$1 \cdot 2 \times 10^{40}$ erg/sec.

(*d*) *NGC 5128 and NGC 1316*

de Vaucouleurs' (1953) suggestion that these two galaxies appear to be similar has been criticized by Baade and Minkowski (1954*b*), who consider that the faint absorption patches of NGC 1316 are quite dissimilar to the heavy absorption band crossing NGC 5128. NGC 1316 is now included on Plate 11 of the Cape Photographic Atlas of Southern Galaxies and large patches of absorption are seen near the edge, even on this long-exposure photograph. Taken in conjunction with Baade and Minkowski's pictures, it appears quite likely that these absorption patches are confined to a band across the galaxy. It is clear from other observations by Minkowski (personal communication to Dr. B. Y. Mills), particularly of spectra, that there are definite differences between the two galaxies as observed optically. On the other hand, there does seem to be some similarity, and it appears that at present we cannot decide, on optical evidence alone, whether or not there is any fundamental similarity which would provide an explanation of their remarkable radio properties.

The Cape Atlas gives the extension of NGC 1316 as 6 min of arc, which would correspond to a length of 8700 pc at the adopted distance. Baade and Minkowski (1954*a*) can trace faint extensions of NGC 5128 over 30 min of arc, corresponding to a length of 6500 pc. Photoelectric recordings by de Vaucouleurs (1956) suggest that extremely faint extensions of this galaxy may be detected over about twice this distance, but no similar observations are available for NGC 1316.

TABLE 1

COMPARISON BETWEEN CENTAURUS-A AND FORNAX-A

	Centaurus-A	Fornax-A
Associated galaxy	NGC 5128	NGC 1316
Optical peculiarities	heavy absorption band	absorption patches in band across galaxy
Adopted distance (pc)	$7 \cdot 5 \times 10^5$	5×10^6
Absolute magnitude (pg)	—18	—19
Max. linear dimensions		
(optical) (pc)	$6 \cdot 5 \times 10^3$	$8 \cdot 7 \times 10^3$
(radio) (pc)	10^5	$\sim 10^5$
Ratio of length to breadth (radio)	3	>2
Radio-frequency spectral index for whole source	$-1 \cdot 0$	-1
Power radiated between 10 and 3000 Mc/s (erg/sec)	3×10^{39}	12×10^{39}
Ratio of 85·5 Mc/s and photographic flux densities	$1 \cdot 1 \times 10^3$	$1 \cdot 8 \times 10^3$

(*e*) *Summary of Evidence for the Similarity of Centaurus-A and Fornax-A*

The observational data on the two sources are collected together in Table 1. Some of the values in the table are based on the assumption that the distances adopted in Section III (*a*) are correct. As an example of the effect of changing the distance of one of the sources, if the distance of NGC 1316 were reduced to about 3×10^6 pc, so that its absolute magnitude was the same as that of NGC 5128, its linear dimensions would be $5 \cdot 5 \times 10^3$ pc (optical) and 6×10^4 pc (radio), and the radiated power would be about 5×10^{39} erg/sec.

All the data of Table 1 are consistent with the hypothesis that, although there may be differences in detail, Centaurus-A and Fornax-A are similar objects physically. Taken together, they would appear to offer some support to this hypothesis, but further optical evidence and the study of the relationship between these and other "radio galaxies", such as M 87 (Virgo-A), (see Section IV), are required before it can be considered as definitely established. If it is accepted, the interpretation of NGC 5128 as a pair of colliding galaxies (Baade and Minkowski 1954*a*) would then appear to be ruled out, as such a description could hardly be applied to NGC 1316.

IV. Further Discussion of Centaurus-A

Because it has such a large angular size, the extended component of Centaurus-A can be studied in some detail with the Cross equipment, and we shall now use the 19·7 and 85·5 Mc/s observations to see what information can be obtained about the structure of this extended source and its association with NGC 5128. It will be assumed in the subsequent discussion that the radiation originates in the acceleration of relativistic electrons in magnetic fields. On this assumption, and using the experimental evidence available at the time,

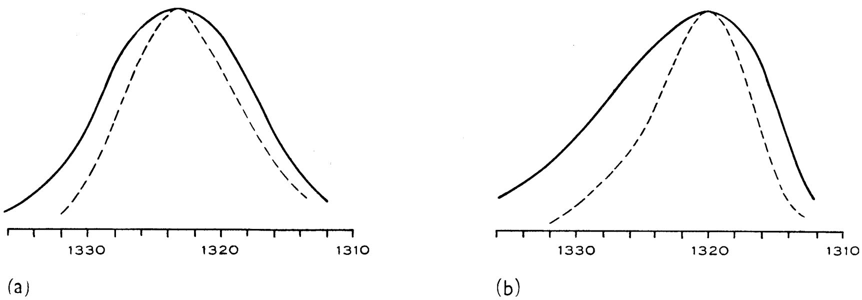

Fig. 5.—Sections across Centaurus-A at two declinations: (*a*) —41°, (*b*) —44°·5. The full and dashed curves are 19·7 and 85·5 Mc/s observations respectively.

Burbidge and Burbidge (1957) have already calculated the total particle and magnetic field energies required to produce the observed emission. These energy estimates depend on the square of the adopted distance to the source, but they are not very sensitive to the values of the spectral indices of the source components. As Burbidge and Burbidge adopted a very large value of the distance, it is thought that the energies they deduced are rather too high, by about one order of magnitude, but otherwise the new data do not appear to affect their general argument.

In Section III (*a*) it was stated that the extended source appears to be wider at 19·7 than at 85·5 Mc/s. The source lies almost along an hour circle, so Figure 5 shows sections across the source at declinations —41° and —44°·5, the scales being adjusted so that the maxima coincide.* From this figure we find for the angular width to half power at the two declinations: 1°·9 and 1°·6 at 85·5 Mc/s; 2°·6 and 2°·8 at 19·7 Mc/s. These are all about twice the aerial

* An approximate allowance for the general background radiation has been removed from the 85·5 Mc/s data using information kindly supplied by Mr. Sheridan. Any small uncertainties in doing this do not affect Figure 5.

beamwidths, so that the corrections for the width of the aerial beams are small (about 0°·2 at 85·5 Mc/s and 0°·4 at 19·7 Mc/s). In Figure 5 it is also seen that the positions of the maxima are the same at the two frequencies but the maximum for one declination is displaced from the maximum for the other declination.

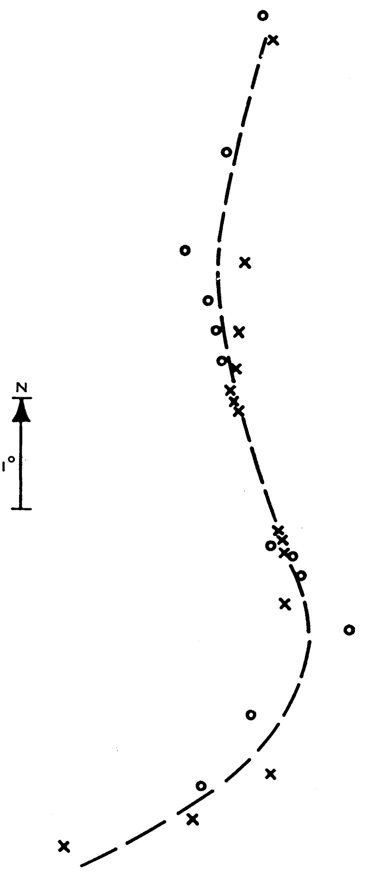

Fig. 6.—Showing the spiral shape of the extended component of Centaurus-A. The heavy dashed line shows the ridge line of the source through the circles (19·7 Mc/s observations) and crosses (85·5 Mc/s observations).

Sheridan has already remarked that the extended source has a shape suggestive of an open spiral. This shape is not so marked at 19·7 Mc/s (see Fig. 3); it would be masked by the faint but more extensive regions observed at this frequency. Nevertheless, there is a suggestion of a spiral shape and to bring this out Figure 6 has been drawn. In this figure, the " ridge line " of the extended source has been drawn by locating the points on the contours at which the curvature is a maximum—a simpler procedure than the drawing of sections as in Figure 5, but giving the same result. The region very close to the central concentration was not considered. Both 85·5 and 19·7 Mc/s data agree well, and the heavy dashed line drawn through the points shows a definite spiral shape.

The spiral is asymmetrical about the centre, but optical photometric studies of NGC 5128 (Evans 1949; de Vaucouleurs and Sheridan 1957) suggest that the nebula is being viewed from the south. (The dark band appears slightly to the north of the centre of the bright nebula, and the southern part is brighter than the northern.)

The plausible model of the extended source is then a spiral, slightly more open than that indicated by Figure 6, with the south-following end nearer the observer and with the plane of the spiral inclined to the line of sight. Asymmetry is produced because the great extent of the source means that the two arms are at different distances and are viewed at different angles. On any model, the greater width at 19·7 Mc/s is readily explained by a weakening of the magnetic fields near the edge of the system and the gradual loss of energy by the highest energy electrons as they diffuse outwards from the centre.

We may note that the apparent position angle of the central part of the spiral is within 10° of the major axis of the main body of the nebula as shown in a long-exposure photograph reproduced by Baade and Minkowski (1954*a*). This might suggest that the extended source is associated with the bright part of the nebula and the central concentration with the dark band (Mills 1953). Alternatively, it is possible that the ends of the dark band curl around into this direction; the whole source would then have a barred spiral structure with a bright concentration in the very small bar. It is not possible to study such detail near the centre with the Cross equipment, but that some complication is present in that region is clear from Mills's (1953) interferometer observations. The whole question is complicated by the fact that the dark band and the major axis of the nebula are very nearly at right angles. This may well mean that the shape of the nebula (and of the extended source) is somehow intimately connected with the appearance of the dark band.

Any discussion of the origin of the source's spiral shape must be largely speculative until some decision can be made concerning the way in which the electrons (or positrons) responsible for the radio emission reach their high energies. Burbidge and Burbidge (1957) have already shown that the electrons must have been produced at high energies, since acceleration processes are too inefficient. An estimate of the number density of the particles actually responsible for the emission can be obtained by using the theory outlined by Ginzburg (1956). We then find that if the magnetic field is 10^{-5} G the particle density is 4×10^{-13} cm^{-3}, whilst for a magnetic field of 10^{-6} G it is 7×10^{-11} cm^{-3}. The total number of particles would be about 10^{57} or 10^{59} respectively, and even if there were an equal number of particles of protonic mass the total rest mass would be only 1 or 100 solar masses. Of course, the mass of the extended source may well be much higher than this. For example, Burbidge and Burbidge considered in detail the production of the high-energy electrons by collisions of a primary high-energy proton flux with static gas and dust in the extended source, and their assumed density of about 10^{-26} g/cm³ (about 0·01 proton/cm³) leads to a mass of about 10^{10} solar masses. This would be an appreciable part of the mass of the NGC 5128 system and the general theory of galactic structure would have to be considered.

On the other hand it is possible that the radiating particles are themselves ejected at high energy from the galaxy, so that the mass of the source is extremely small. Then the spiral shape is a consequence of the rotation of the nucleus through roughly one-quarter of a revolution since the start of the ejection. Using Mayall's (1948) data on rotation periods of galaxies, the age of the extended source would be about 10^7 years, and the arms would expand at the rate of about 3000 km/sec. In this regard, it is noteworthy that Baade and Minkowski (1954*a*) quote spectral observations, by Humason, of M 87 (identified with the radio source Virgo-A) which suggest that the matter in the jet emerging from the nucleus of this galaxy is being ejected at speeds of the order of 500 km/sec. They estimate the age of the jet to be about 10^6 years. These figures would seem to favour Burbidge and Burbidge's suggestion that M 87 represents an early stage in the development of a system such as NGC 5128. This suggestion ties in with the hypothesis of Ambartsumian (1958) that NGC 5128 is actually a galaxy in the process of division.

It would be very interesting if a detailed spectroscopic study of NGC 5128 gave evidence of a rotation of the system consistent with this interpretation of the radio data observations. In fact, such a study would seem to be very desirable just to supplement the meagre optical information at present available.

V. Acknowledgments

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VI. References

Allen, C. W. (1955).—"Astrophysical Quantities." (Athlone Press: London.)

Ambartsumian, V. A. (1958).—"The Large-scale Structure of the Galactic System." I.A.U. Symposium No. 5, pp. 4–6. (Cambridge Univ. Press.)

Baade, W., and Minkowski, R. (1954*a*).—*Astrophys. J.* **119**: 215–31.

Baade, W., and Minkowski, R. (1954*b*).—*Observatory* **74**: 130–1.

Bailey, D. K. (1948).—*Terr. Mag. Atmos. Elec.* **53**: 41–50.

Bolton, J. G., Westfold, K. C., Stanley, G. J., and Slee, O. B. (1954).—*Aust. J. Phys.* **7**: 96–109.

Burbidge, G. R., and Burbidge, E. M. (1957).—*Astrophys. J.* **125**: 1–8.

Evans, D. S. (1949).—*Mon. Not. R. Astr. Soc.* **109**: 94–102.

Ginzburg, V. L. (1956).—*Nuovo Cim.* **3** (Suppl. No. 1): 38–48.

Haddock, F. T., Mayer, C. H., and Sloanaker, R. M. (1954).—*Astrophys. J.* **119**: 456–9.

Hagen, J. P., McClain, E. F., and Hepburn, N. (1954).—*Proc. Inst. Radio Engrs., N.Y.* **42**: 1811.

McGee, R. X., Slee, O. B., and Stanley, G. J. (1955).—*Aust. J. Phys.* **8**: 347–67.

Mayall, N. U. (1948).—*Sky & Telesc.* **8**: 3–5, 17.

Mills, B. Y. (1952).—*Aust. J. Sci. Res.* A **5**: 266–87.

Mills, B. Y. (1953).—*Aust. J. Phys.* **6**: 452–70.

Piddington, J. H., and Minnett, H. C. (1951).—*Aust. J. Sci. Res.* A **4**: 459–75.
Piddington, J. H., and Trent, G. (1956).—*Aust. J. Phys.* **9**: 74–83.
Shain, C. A. (1958).—*Proc. Inst. Radio Engrs., N.Y.* **46**: 85–8.
Shain, C. A., and Higgins, C. S. (1954).—*Aust. J. Phys.* **7**: 130–49.
Sheridan, K. V. (1958).—*Aust. J. Phys.* **11**: 400–8.
Smith, F. G. (1952).—*J. Atmos. Terr. Phys.* **2**: 350–5.
Stanley, G. J., and Slee, O. B. (1950).—*Aust. J. Sci. Res.* A **3**: 234–50.
de Vaucouleurs, G. (1953).—*Observatory* **73**: 252–4.
de Vaucouleurs, G. (1956).—*Occ. Notes R. Astr. Soc.* **3**: 118–42.
de Vaucouleurs, G., and Sheridan, K. V. (1957).—"Radio Astronomy." I.A.U. Symposium No. 4, p. 169. (Cambridge Univ. Press.)