BRIGHTNESS DISTRIBUTION IN DISCRETE RADIO SOURCES
IV. A DISCUSSION OF 24 IDENTIFIED SOURCES

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ABSTRACT

Radial distances, linear dimensions, and total luminosities are given for 24 identified extragalactic radio sources, 19 of which have measured radial velocities. Using the synchrotron theory, the total energy and magnetic-field strength required to account for the observed luminosity are estimated for each source. Eight sources are found with energy requirements exceeding 10^{60} ergs. Typical field strengths are $\sim 10^{-5}$ oersted. The linear diameters range from less than 1 to 290 kpc. Illustrations of the radio and optical brightness distributions are given for 11 sources.

I. INTRODUCTION

At present there is no way of determining the distance of a radio source from radio observations alone. Thus it is fortunate that a number of radio sources can be identified with optical objects, because the optical red shift is known to be a reliable distance indicator. If the distance of a source is known, the observed radio intensities and brightness distributions can be used to obtain the total luminosity and the projected linear dimensions of the emitting regions. Estimates can then be made of the physical conditions within the source.

In previous papers, observations of radio-source brightness distributions at a wavelength of 31 cm have been described (Moffet 1962, Paper I; Maltby 1962, Paper II), and radio descriptions of a number of extragalactic sources have been given (Maltby and Moffet 1962, Paper III). Identifications are available for some of these objects, and in the present paper we consider a group of 24 identified sources for which the radio positions and brightness distribution data are complete, or nearly so. The identifications are used to provide distances and hence to obtain some of the intrinsic parameters of the radio sources. The radio positions, measured with the Caltech interferometer (Matthews and Read, in preparation), have been combined with the radio brightness distributions to show the relative location of radio and optical counterparts in the various types of sources.

The 24 sources considered here include some previously identified sources (see Bolton 1960), as well as some new identifications which have resulted from the Caltech programs of position and brightness distribution measurements. These and other identifications will be the subject of a forthcoming article by Matthews; hence a detailed discussion of the evidence for these particular identifications will not be given here.

II. OBSERVATIONAL DATA

Optical and radio data for the sources are given in Table 1. Column 1 contains the name or 3C catalogue number (Edge, Shakeshaft, McAdam, Baldwin, and Archer 1959) of each source, while column 2 gives NGC numbers, where they exist, for the associated optical objects. In column 3 are given the photographic magnitudes of the optical objects. These were estimated for us by E. R. Herzog from the blue plates of the National Geographic Society–Palomar Observatory Sky Survey. The estimates should be correct to within 0.5 mag. for galaxies brighter than $m_{pg} = 17$, with a somewhat greater uncertainty for fainter objects.

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TABLE 1—OPTICAL AND RADIO PROPERTIES OF 24 IDENTIFIED SOURCES

SOURCE	NGC	m_{pg}	cz	$r \cdot h$ (Mpc)	M_{pg} $-5 \log h$	EMISSION LINES	SOURCE TYPE	PROJECTED SOURCE DIMENSIONS: Angular Diameter (′)	Angular Separation (′)	$h \cdot$ Linear Diameter (kpc)	$h \cdot$ Linear Separation (kpc)	RADIO SIZE/OPT. SIZE: Diam.	Sep.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
3C 33		15.7	17800[a]	178	−20.9	em!	U		3.8		200		19
3C 40.	541–545 547	13 4+13.2 +13 4	5320[b,c]	53	−20.7	—	U		5.7		88		6
3C 66.		14.2	6450[c]	65	−20.8	—	U		6.6		125		11
3C 71.	1068	9.5	1130[d]	11	−20.9	em!	N	<0.5		<1.6		<0.1	
3C 75.		14.9+15.2	7220[c]	72	−19.8	—	E	1.2+1.2	2.8	25+25	59	7+7	17
3C 78.	1218	14.8		(98)			S	1.0		(29)		3	
For A.	1316	9 6	1730[d]	17	−21.8	—	U	18+18[k]	29[k]	89+89	140	9	13
3C 98.		15.3	9200[a]	92	−20.0	em	U		3 4		91		14
3C 198.		17.8	25000[a]	250	−19.8	em!	H	<1+3.5		250		70	
Hyd A.		15.1	15900[c]	160	−21.5	em	H	1.0+5.0		46+230		10+50	
3C 219		19 4	52000[a]	520	−19 6	em!	E	0.85+0.85	1.9	130+130	290	14+14	30
3C 270.	4261	12.0	2090[d]	11*	−18.5	—	E	2.7+2.7	4.7	8.6+8.6	15	2+2	3.5
Vir A.	4486	10.0	1220[d]	11*	−20.5	em	H	0.6+6.5		1.9+21		0.3+3.5	
3C 278.	4782–3	13.2+13.6	4300[e]	43	−20.3	—	S	2.2		28		3.5	
Cen A.	5128	7.5	470[d]	4[j]	−21.3	em	{E {U	3+3 100+100[l]	7.1 200[l]	3.5+3.5 120+120	8.3 240	0.25 5	0.6 10
3C 295.		20.9[f]	138000[f]	1380	−20.1	em!	N	0 08[m]		32		~3	
3C 310.		16.2+16.2		(200)			(E)		2.1		(120)		21
3C 315.		17.8+18.3		(390)			(S)	1.2		(140)		10	
3C 327		17.2		(280)			U		3.5		(290)		21
3C 338.	6166	13.6[g]	9080[g]	91	−21.6	em	S	1.2		32		8	
Her A.		19.3	46200[h]	460	−19.5	em!	E	0.75+0.75	1.95	100+100	260	10+10	25
3C 353.		13.5[c]		(65)			U	1.4+1.4	≥2.5	(26+26)	(≥50)	8+8	~15
Cyg A.		15.1[i]	17100[i]	170	−21.1	em!	E	0.7+0.7	1.58	35+35	79	4+4	10
3C 442.	7236–7	14.5+13.8	7860[h]	79	−21.1	em	S	3.0		69		10	

NOTES TO TABLE 1

* Assumed distance for the Virgo Cluster.
[a] M. Schmidt, private communication.
[b] Zwicky (1961).
[c] Minkowski (1961*b*), corrected velocities for 3C 40, 3C 66, and 3C 75 from private communication; M_{pg} for 3C 353 corrected for 4^m absorption.
[d] Humason, Mayall, and Sandage (1956).
[e] Greenstein (1961).
[g] Minkowski (1961*a*).
[h] Greenstein (1962).
[i] Baade and Minkowski (1954*a*), M_{pg} corrected for 2.1^m absorption.
[j] Sersic (1960).
[k] Wade (1961).
[l] Bolton and Clark (1960).
[m] Allen, Palmer, and Rowson (1960).

Radial velocities for 19 of the selected objects are listed in column 4, together with references indicating their origin. Seven of these measurements have been made recently at the Palomar Observatory and have been communicated to us in advance of publication. We are deeply indebted to Drs. M. Schmidt, J. L. Greenstein, and R. Minkowski for permission to make use of these important results.

On assuming a value for the Hubble parameter of $H_0 = 100\,h$ km s^{-1} Mpc^{-1}, the radial velocities have been converted to the distances given in column 5. The distances and the apparent magnitudes have been used to derive absolute magnitudes, as given in column 6. The absorption within our own galaxy was assumed to be 0.25 csc b mag. In the cases where the radio source is identified with a multiple galactic system, the absolute magnitude of the brightest component has been given. No redshift correction has been applied to the absolute magnitudes, as it is not entirely clear that the usual redshift corrections are applicable without modification. The more distant objects, for which this correction would be greater than a few tenths of a magnitude (Humason, Mayall, and Sandage 1956), all have spectra characterized by strong emission lines. However, there seems to be no significant difference in absolute magnitude between objects with normal spectra and objects with spectra showing strong emission lines.

The mean of the absolute magnitudes in column 6 is $\bar{M}_{pg} - 5 \log h = -20.5$, with a standard deviation of 0.8 mag. Approximate distances have been derived for the remaining five galaxies on the assumption that they have absolute magnitudes equal to this mean. These distance values, inclosed in parentheses, are given in column 5. If the true M_{pg} of one of these objects should differ from the assumed mean value by an amount equal to the standard deviation in the mean, the derived distance would be in error by a factor of 1.5.

In column 7 the presence of strong emission lines in the optical spectrum is indicated by *em*!. If emission lines are present but not strong, an *em* is entered. A dash indicates that no emission lines are observed in the spectrum.

The letters in column 8 give the structural classification of the sources, as defined in Paper III. Sources with two equal intensity components are designated by an "E"; sources with unequal components by a "U"; core-and-halo objects by an "H"; simple, roughly circular sources by an "S"; and objects which were not resolved in our investigation by an "N." Columns 9 and 10 contain the angular dimensions of each source, while the corresponding linear dimensions in the plane perpendicular to the line of sight are given in columns 11 and 12. The radio diameters refer to half-intensity diameters of Gaussian models approximating the various components of the sources. Full details have been given in Paper III.

For each source the ratios of the radio dimensions to the optical diameter of the galaxy identified with the source are given in the last two columns. If more than one galaxy is involved, then the optical diameter refers to the largest galaxy of the group. The angular diameters of the galaxies were measured on the red plates of the Sky Survey. The true extent of a galaxy is several times larger than the size measured on the Sky Survey plates (Humason, Mayall, and Sandage 1956, Appendix A). The over-all extent of a radio source is also several times greater than the half-intensity diameter. Thus the ratios in column 13 should be reasonable comparisons of radio and optical diameters, while those in column 14 may exaggerate the separation of the radio source from the galaxy.

The distance of an object with red shift $z = \Delta\lambda/\lambda$ has been assumed to be equal to cz/H_0. In fact, the distances which should be used in determining linear dimensions and distance moduli contain additional terms which are non-linear in z (see, for example, Sandage 1961*a*). The coefficients of these additional terms depend on the cosmological model which correctly describes the universe, and a wide choice of models is compatible with current observational data (Sandage 1961*b*). Hence no attempt has been made to include these non-linear terms. The general effect would be to make the distant objects smaller and brighter than is indicated in Table 1. Some specific examples will be given in connection with the computation of the energies of the sources.

Figures 1, 2, and 3 give combined radio and optical pictures of several of the sources, indicating the position of the radio-emitting regions with respect to the associated galaxies. The circles indicate the approximate size of the various radio components. In the asymmetrical double sources there is more uncertainty about the component sizes, and they are indicated with dashed circles. The numbers give the relative intensities of the components. The photographs of the galaxies in Figures 1 and 2 have been copied from the red plates of the Sky Survey. The photograph of NGC 5128 in Figure 3 was copied from a red plate taken with the 48-inch Schmidt telescope by R. Minkowski.

III. REMARKS ON INDIVIDUAL SOURCES

The following remarks will serve to describe the objects in Figures 1–3 and to give references for those identifications which have previously been reported.

3C 33.—This identification was first suggested by Dewhirst (see Elsmore 1959). As can be seen in Figure 1, *a*, the galaxy lies very close to the centroid of the radio emission.

3C 40.—Minkowski (1958) originally suggested that this source might be associated with the close pair of elliptical galaxies NGC 545–547, although he pointed out that an accurate position by Mills was definitely earlier in right ascension. Our position and brightness distribution, shown in Figure 2, *a*, indicate that the source has two unequal components, with the radio centroid southwest of NGC 545–547 in the direction of a third elliptical galaxy, NGC 541. According to Zwicky (1961), there is a luminous bridge connecting NGC 545–547 to NGC 541, with a fainter extension toward the spiral seen in the lower right-hand corner of Figure 2, *a*. It seems possible that all three galaxies, which are the brightest members of a cluster, may be associated with the source.

3C 66.—The identification of this source with a single galaxy having a jetlike feature is due to Minkowski (quoted by Harris and Roberts 1960; see also Bolton 1960). The radio structure, shown in Figure 2, *b*, very much resembles that of 3C 40. In this case, however, the galaxy lies close to the radio centroid.

3C 71.—This source has been identified with the well-known Seyfert galaxy NGC 1068 (Seyfert 1943; Mills 1955; Burbidge, Burbidge, and Prendergast 1959; Woltjer 1959). The position and diameter measurements confirm the suggestion of Burbidge *et al.* and of Woltjer that the radio emission comes from the nucleus of the galaxy. The radio spectrum is remarkably flat.

3C 75.—Minkowski (1960*a*) suggested that this source could be identified with a close pair of galaxies. As can be seen in Figure 1, *b*, the radio source consists of two roughly equal components whose centroid falls about 1′ northeast of this pair. Closer to the radio centroid there is an inconspicuous galaxy of about $m_{pg} = 18$, but for the purposes of this paper we shall assume that the correct identification is the fifteenth-magnitude pair. Recent measurements by Read (private communication) indicate that the source components may not be so nearly symmetrical as was indicated in Paper III. The position of the radio centroid will not be changed appreciably, however. It is possible that another member of the cluster of galaxies, of which the double is a member, may also be associated with the radio source.

3C 78.—The identification with NGC 1218 has been noted by Mills (1960) and by Bolton (1960). Figure 1, *c*, shows that the radio structure is simple and fits nicely over the galaxy.

Fornax A.—The radio source is large, about 1° in over-all extent, and is thus heavily resolved by the Caltech interferometer at its closest spacing. Wade (1961) has shown that the source has two components of unequal intensities and diameters. The centroid of the radio emission lies within the optical boundaries of NGC 1316. The identification with NGC 1316 was suggested independently by Shklovskii and by de Vaucouleurs (see the review by Minkowski 1957).

3C 98.—The CTA position measurements first suggested this identification (Harris

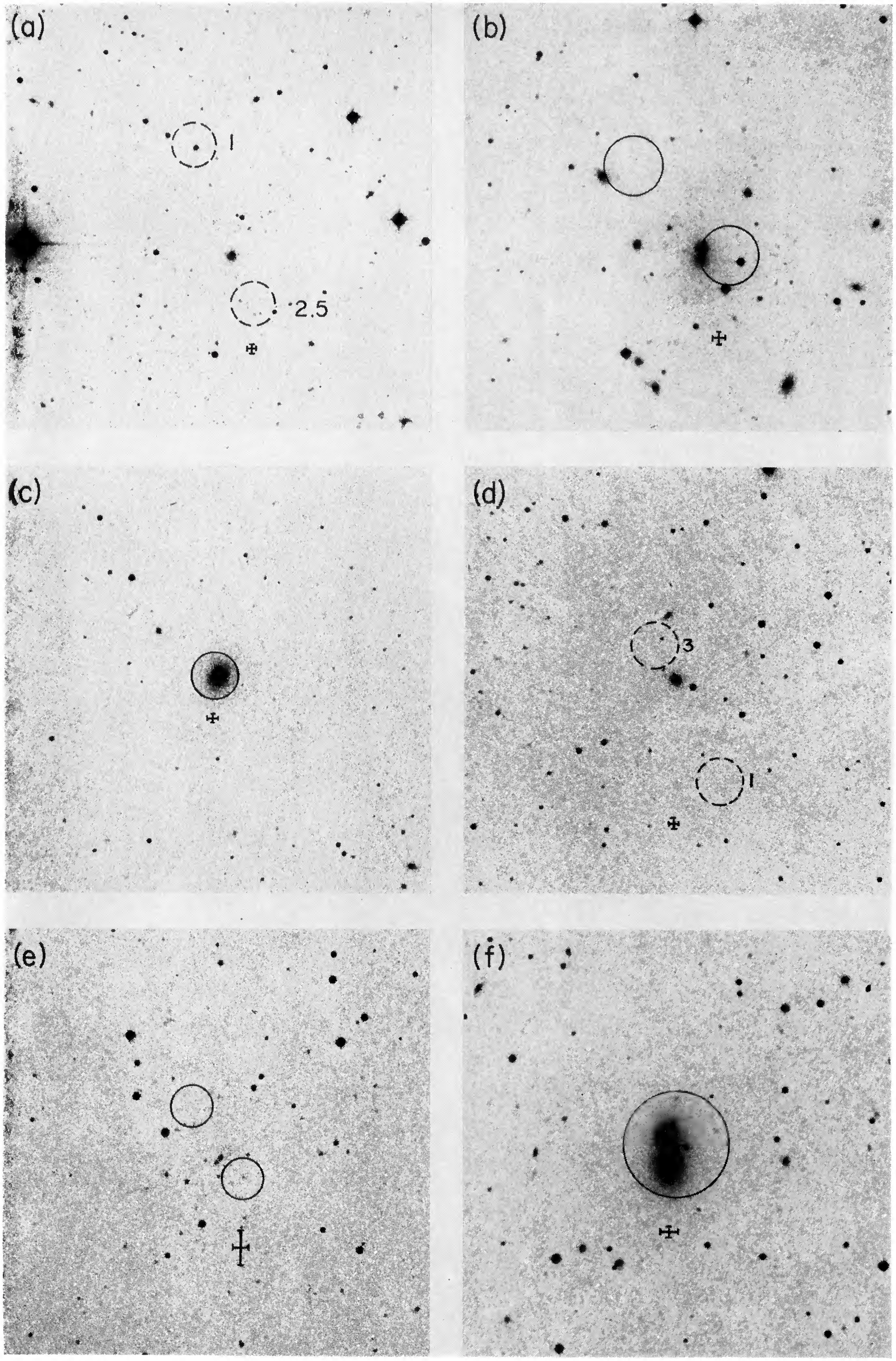

FIG. 1.—Radio and optical brightness distributions for (*a*) 3C 33, (*b*) 3C 75, (*c*) 3C 78, (*d*) 3C 98, (*e*) 3C 219, (*f*) 3C 278. The cross below each source indicates the probable error limits in the placement of the radio object with respect to its optical counterpart. North is at the top, and east is to the left. Each field is 10′ × 10′.

1963ApJ...137..153M

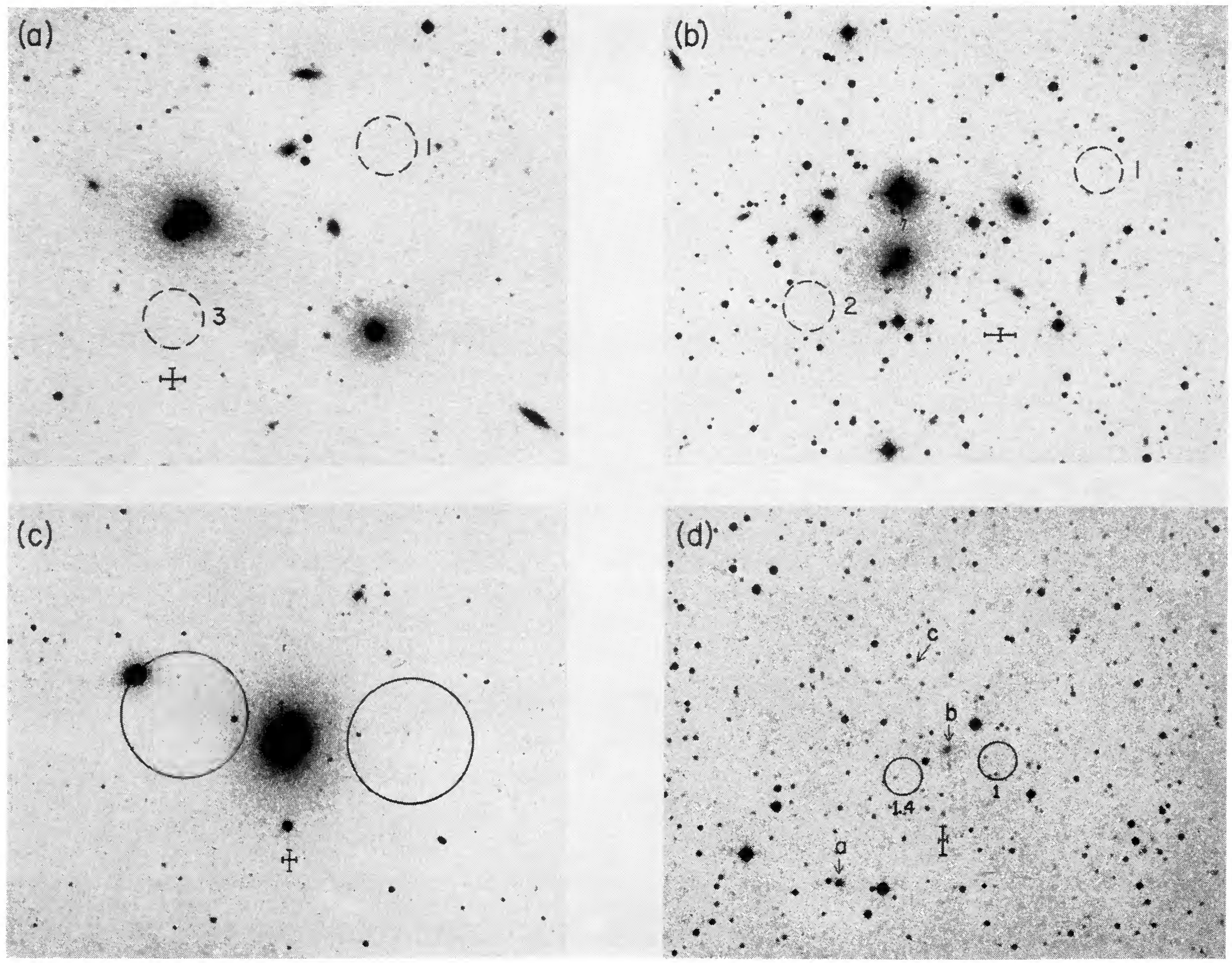

FIG. 2.—Radio and optical brightness distributions for (*a*) 3C 40, (*b*) 3C 66, (*c*) 3C 270, (*d*) Hercules A. Each field is 10′ × 12′. See legend for Fig. 1 for other details.

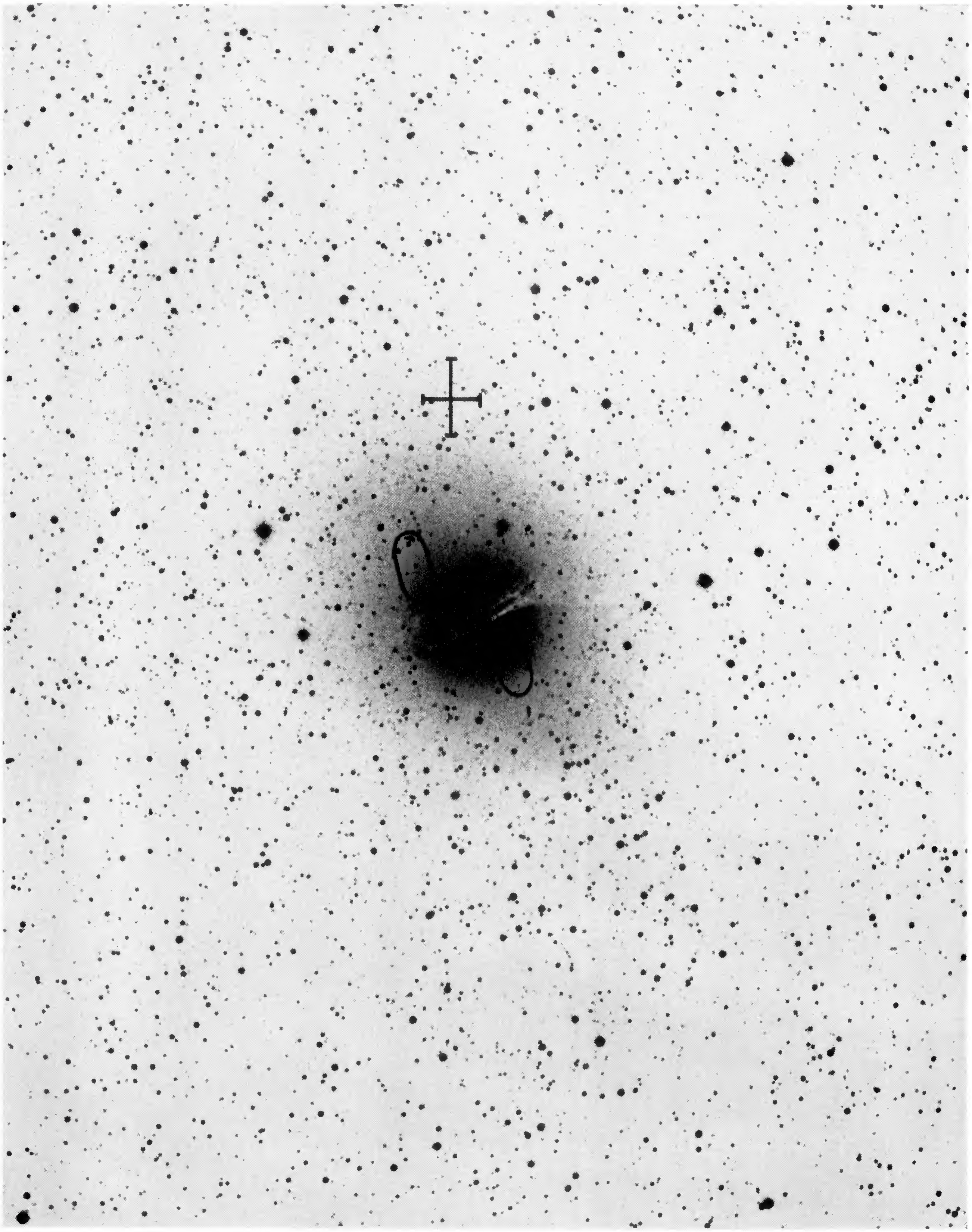

FIG. 3.—Radio brightness distribution for the central component of Centaurus A superposed on a photograph of NGC 128. Field is 50′ × 40′. See legend for Fig. 1 for other details.

and Roberts 1960; Bolton 1960), and it now seems quite certain. The centroid of the unequal double source lies very close to the galaxy, as is shown in Figure 1, *d*.

3C 198.—The radio source consists of a 3′.5 halo with a rather faint core of small diameter. It coincides in position with a loose cluster of galaxies. The brightest member of this cluster has a slightly asymmetrical image on the red Sky Survey plate, and Schmidt has found strong emission lines in its spectrum. The ratio of radio to optical size for this source is particularly large; the linear diameter of the radio source of 250 h^{-1} Mpc is among the largest known.

Hydra A.—The source consists of a large halo with a non-circular core. Measurements by Lequeux and Heidmann (1961) have shown that about 20 per cent of the flux from the core originates in a component of very small diameter. The optical identification, first noted by Minkowski, is a very close pair of elliptical galaxies having a common envelope (Dewhirst 1959).

3C 219.—The identification with a pair of nineteenth-magnitude galaxies was suggested by Dewhirst (1959). Figure 1, *e*, shows that the two components of the source straddle these galaxies, which are the two brightest members of a cluster. Sandage has obtained a red plate with the 200-inch telescope, and it shows that the fainter, southern member of the pair has jetlike extensions in position angles 120° and 240°. In addition, there is a faint bridge between the galaxies. A spectrum obtained by Schmidt shows that the northern object has strong emission lines. The linear size and the ratio of radio to optical size are both very large.

3C 270.—The identification with NGC 4261 is due to Mills, Slee, and Hill (1958). It seems to be well confirmed by the present data, as shown in Figure 2, *c*. The galaxy is a normal elliptical.

Virgo A.—This was one of the very earliest identifications (Bolton, Stanley, and Slee 1949). Extensive optical studies have been reported by Baade and Minkowski (1954*b*), Baade (1956), and Hiltner (1959). The radio measurements, which were reviewed in Paper III, show that a 7′ halo surrounds a small-diameter core that is presumably to be associated with the jet in NGC 4486. The measurements of Lequeux and Heidmann (1961) have shown that the core consists of two components with an east-west spacing of 0′.5. Baldwin and Smith (1956) have found evidence at meter wavelengths for a very extended halo component with a diameter of about 50′. In the absence of spectral information about this component, we shall ignore it in computing the total energy requirements for the radio source. The core will be assumed to consist of two cylindrical components, each 1.5 h^{-1} kpc long and 0.6 h^{-1} kpc in diameter.

3C 278.—The identification with the close pair of galaxies NGC 4782–4783 was first suggested by Mills, Slee, and Hill (1958). The galaxies have been discussed by Greenstein (1961). Figure 1, *f*, shows that they lie, at least in projection, within the single radio source.

Centaurus A.—The identification with NGC 5128 was made by Bolton, Stanley, and Slee (1949). Optical data on this galaxy have been given by Baade and Minkowski (1954*b*) and by Burbidge and Burbidge (1959). The radio emission comes from two extended regions on opposite sides of the galaxy and from two small regions situated within the galaxy (see review in Paper III; also Maltby 1961). The central source is shown superposed on the galaxy in Figure 3. The photograph was printed rather darkly, in order to show the outer regions of the galaxy. The major axis of the central radio source is seen to correspond roughly with the direction of elongation of these outer regions.

3C 295.—This object has been discussed by Minkowski (1960*b*). Allen, Palmer, and Rowson (1960) have found its east-west angular diameter at meter wavelengths to be 4″.5. Although the brightness distribution is not well known, this source has been included here because of its high luminosity and its relatively small ratio of radio to optical diameter. In order to calculate the energy requirements, we shall assume that the source is spherical, with an angular diameter equal to the measured east-west diameter.

3C 310, 3C 315.—These identifications were made by Dewhirst (1959) and are confirmed by subsequent position measurements. Data on the radio structure of these sources are not so complete as for most of the others in Table 1.

3C 327.—The identification was given by Bolton (1960). Our radio position and brightness distribution differ from those published by the Cambridge group (Elsmore, Ryle, and Leslie 1959; Leslie 1961), but the latter measurements were probably influenced by the source of comparable intensity situated about 1° to the southeast.

3C 338.—The identification with the NGC 6166 group of galaxies has been discussed in detail by Minkowski (1958, 1961). The radio source is of class S and agrees well in position with the group of galaxies.

Hercules A.—The correct identification seems to be that suggested by Williams, Dewhirst, and Leslie (1961, their "object b"). It is confirmed by our position and brightness distribution measurements and by a spectrum taken by Greenstein (1962). As seen in Figure 2, *d*, the galaxy, which has an unusual distribution of intensity, lies near the centroid of the two radio components. The sharp image 3″.3 northwest of the galaxy is probably a foreground star.

3C 353.—A seventeenth-magnitude elliptical galaxy noted by Mills (1960) agrees well with the position of this strong source. The amount of galactic absorption and hence the distance derived from the apparent magnitude are rather uncertain.

Cygnus A.—The optical features of this object have been described by Baade and Minkowski (1954*a*); the radio features are summarized in Paper III.

3C 442.—This source in many ways resembles 3C 278. A spectroscopic investigation of NGC 7236–7237 is described by Greenstein (1962).

IV. RADIO AND OPTICAL PROPERTIES

The sources shown in Figures 1–3 illustrate the variety of combinations of radio and optical structure that seem to occur. Not all the combinations are illustrated, since no example of the core-and-halo type of radio source is shown. Among the examples available so far, there seem to be no particular correlations of the optical appearance (e.g., close double galaxy, single galaxy, distortions, etc.) with any of the classifications of radio structure. The galaxies identified with radio sources exhibit a wide range of peculiarities on the direct photographs. Some galaxies have unusual absorption features, while others have barely visible jetlike features. A few of the identifications show no peculiarities. Some of the identifications are close binary or multiple systems of galaxies which are imbedded in a common envelope. A few of these pairs of galaxies have highly distorted envelopes and nuclei. More subtle peculiarities will undoubtedly be noticed when the galaxies are studied more intensively (see below).

As was shown in Paper III, an important result of the present investigation of source brightness distributions is that a majority of all the extragalactic sources consist of two widely separated components. The examples of this type of source which have been illustrated in the present paper show that in these cases the radio-emitting regions are usually well separated from the associated galaxy. The galaxy is typically found at, or very close to, the centroid of the radio emission. A few cases in which the optical object may be displaced from the radio source have already been noted and discussed in Section III.

Spectral information is available for 19 of the identifications listed in Table 1. Ten of these show unusually strong emission lines; the others show no spectral peculiarities. There seems to be a correlation between the intrinsic radio emission from the source and the occurrence of unusually strong emission lines in the spectrum. The probability of occurrence of the λ 3727 emission line in elliptical galaxies (Osterbrock 1960) is near 15 per cent, and the strength of the emission line is from weak to moderate. The seven sources in Table 2 having $L \gtrsim 5 \times 10^{41}$ ergs/sec and for which spectra exist, all have strong to very strong emission lines. Of the nine sources having $L \lesssim 5 \times 10^{41}$ ergs/sec and for which spectra exist, two (3C 71 and Vir A) have strong emission lines, three (Cen

A, 3C 338, and 3C 442) have emission lines of the intensity found occasionally in normal ellipticals, and the other four show no emission lines in their spectra. The frequency of occurrence of emission lines is higher in the later-type systems, and so the significance of the above remarks must await a discussion of galaxy types and of the emission spectra.

Many of the radio sources are much larger than the size of the galaxy involved; some are only a few times the optical size. A few are smaller than the associated galaxy; for instance, 3C 71 is less than one-tenth the size of NGC 1068.

Two of the large radio sources—Hydra A and 3C 198—are identified with galaxies in clusters. They are both core-halo type objects, and the linear diameters of the halos are 230 and 250 kpc, respectively. These very large sizes might be due to the influence of other members of the cluster, but we have no indication that this is so. However, with these large sizes it is very probable that one or more other galaxies exist inside the radio-emitting region. There are at least two double radio sources having separations >170 kpc whose optical counterparts are members of clusters (3C 219 and 3C 327). Again the sizes are larger than the average separation between the galaxies in clusters.

Several of the galaxies identified with radio sources show an unusual distribution of light across the galaxy. Minkowski (1961*a*) has mentioned the lack of a central concentration in NGC 6166, and Greenstein (1961, 1962) has found similar unusually flat light-distributions in NGC 4782 and NGC 7237, each one a member of a pair of galaxies, and also in the galaxy identified with Hercules A (object b). Several other identifications also show the same effect to a varying degree—for instance, 3C 465 (NGC 7720), 3C 295, 3C 433, and probably 3C 33, 3C 88, and 3C 98. Not all identifications have this property; for instance, M87 seems normal in this respect.

V. LUMINOSITIES AND ENERGY REQUIREMENTS

When the distance of a source is known, as well as its flux density as a function of frequency, the radio luminosity may be calculated. We have done this for the sources described above, using the distances given in Table 1 and spectral information from a variety of observers. We have assumed a simple power-law dependence of the flux over the frequency range of 10^7–10^{10} c/s. The observed intensities have not been corrected for displacements in wavelength due to Doppler shifts because of our limited knowledge of the spectral behavior near the cutoff frequencies. For each source the power emitted (L) between the above frequency limits and the spectral index which gives a best fit to the observed intensities are given in Table 2.

It is seen that the luminosities have a range of nearly five decades, from weak emitters, such as 3C 71 and 3C 270, to the three strongest sources, Cygnus A, 3C 295, and Hercules A. As has already been mentioned, the luminosity distance, which should properly be used in deriving the total luminosity from the observed radiation flux, is a function of the cosmological model. The distance in Table 1 was assumed to be cz/H_0, which happens to be the correct luminosity distance for a closed, elliptical universe characterized by a deceleration parameter q_0 equal to $+1$ (Sandage 1961*a;* see also Sandage 1961*b*). Smaller values of q_0 would yield higher values for the luminosities of the distant sources, with the steady-state model ($q_0 = -1$) giving a correction of $(1 + z)^2$. Thus, in a steady-state universe, 3C 295 would be more luminous than Cygnus A.

It is generally believed that non-thermal radio emission is produced by the synchrotron mechanism. As several authors have demonstrated, the theory of synchrotron emission permits an estimate of the energy requirements for a source, once the emitting volume and the radio luminosity and spectral index are known. Using rather limited data on the physical sizes of radio sources, Burbidge (1959) has already shown that the energy requirements for the more luminous sources are very great. We have thought it worthwhile to repeat these calculations for the sources described in this paper, inasmuch as the information presented here on source sizes and luminosities is considerably more detailed than that which has previously been available. We follow here the derivations of the Burbidges

(G.R. 1956*b;* G.R. and E.M. 1957). Burbidge has given a short discussion of the assumptions underlying these calculations (1956*a*).

It is known that a non-thermal spectrum characterized by an intensity proportional to ν^x, where x is the usual spectral index, may be produced by a cloud of electrons circulating in a magnetic field H (in the following, H denotes the effective magnetic field) and having a number spectrum which varies with energy as E^{2x-1}. Each electron radiates most strongly near its critical frequency, given by $\nu_c \propto HE^2$; hence the cutoff frequencies assumed for the radio spectrum can be used to assign rough cutoff energies for

TABLE 2

REQUIRED MAGNETIC-FIELD STRENGTHS AND ENERGIES

Source	Spectral Index	Emitted Power (ergs/sec)	Volume (cm³)	H (oersted)	E_t (ergs)
3C 33	−0 70	$4\,0\times10^{42}$	$4\,3\times10^{69}$	3×10^{-5}	3×10^{59}
3C 40 .	−0 85	$1\,6\times10^{41}$	1.0×10^{68}	4×10^{-5}	1×10^{58}
3C 66	−0 65	$3\,7\times10^{41}$	$2\,1\times10^{68}$	3×10^{-5}	2×10^{58}
3C 71	−0 25	$7\,4\times10^{39}$	$<6\,4\times10^{64}$	$>9\times10^{-5}$	$<4\times10^{55}$
3C 75 .	−0 65	$2\,8\times10^{41}$	$4\,8\times10^{68}$	2×10^{-5}	2×10^{58}
3C 78	−0.35	7.0×10^{41}	3.7×10^{68}	3×10^{-5}	3×10^{58}
For A	−0 75	$2\,5\times10^{41}$	2.2×10^{70}	8×10^{-6}	1×10^{59}
3C 98.	−0 65	8.6×10^{41}	$6\,0\times10^{68}$	3×10^{-5}	5×10^{58}
3C 198	−0 95	1.6×10^{42}	$2\,4\times10^{71}$	8×10^{-6}	1×10^{60}
Hyd A {core .	−0 65	1.0×10^{43}	$1\,5\times10^{69}$	5×10^{-5}	3×10^{59}
Hyd A {halo	−0 65	1.4×10^{42}	$1\,9\times10^{71}$	1×10^{-5}	3×10^{60}
3C 219	−0 70	$2\,2\times10^{43}$	$6\,7\times10^{70}$	2×10^{-5}	2×10^{60}
3C 270	−0.70	2.3×10^{40}	$2\,0\times10^{67}$	3×10^{-5}	2×10^{57}
Vir A {core	−0 30	1.6×10^{41}	$2\,5\times10^{64}$*	3×10^{-4}	2×10^{56}
Vir A {halo	−0 95	1.3×10^{41}	$1\,4\times10^{68}$	3×10^{-5}	1×10^{58}
3C 278.	−0 85	$1\,4\times10^{41}$	$3\,4\times10^{68}$	2×10^{-5}	2×10^{58}
Cen A {core	−0 70	4.8×10^{40}	$1\,3\times10^{66}$	8×10^{-5}	7×10^{56}
Cen A {halo	−0.95	$1\,6\times10^{41}$	5.3×10^{70}	6×10^{-6}	2×10^{59}
3C 295	−0 50	4.4×10^{44}	$5\,0\times10^{68}$	2×10^{-4}	1×10^{60}
3C 310.	−0 95	3.8×10^{42}	5.7×10^{69}	3×10^{-5}	4×10^{59}
3C 315	−0 80	6.3×10^{42}	$4\,2\times10^{70}$	2×10^{-5}	1×10^{60}
3C 327	−0 75	$6\,5\times10^{42}$	$1\,6\times10^{70}$	2×10^{-5}	7×10^{59}
3C 338	−1 10	$5\,0\times10^{41}$	$5\,0\times10^{68}$	4×10^{-5}	5×10^{58}
Her A	−0 90	$1\,1\times10^{44}$	$3\,1\times10^{70}$	5×10^{-5}	5×10^{60}
3C 353	−0.45	2.2×10^{42}	$5\,0\times10^{68}$	4×10^{-5}	7×10^{58}
Cyg A	−0 75	$4\,4\times10^{44}$	$1\,3\times10^{69}$	2×10^{-4}	3×10^{60}
3C 442	−1 10	2.6×10^{41}	$5\,0\times10^{69}$	2×10^{-5}	1×10^{59}

* Assumed to consist of two cylindrical components, each 1.5 kpc long and 0.6 kpc in diameter.

the electron spectrum. The electron spectrum can then be integrated between cutoffs to give the total electron energy,

$$E_e = C\,\frac{L}{H^2}\left(\frac{2+2x}{1+2x}\right)\frac{E_l^{2x+1}-E_h^{2x+1}}{E_l^{2x+2}-E_h^{2x+2}}.$$

Here E_l and E_h are the low and high cutoff energies, L is the radio luminosity, and C is a constant, approximately equal to 422.3 for c.g.s. units. If the cutoff frequencies are regarded as fixed, while the field strength H is left as a free parameter, the electron energy may be written as

$$E_e = C'LH^{-3/2}\,,$$

where C' now includes a slow dependence on the cutoff frequencies and on the spectral index.

Let α be the ratio of heavy-particle energy, E_p, to the electron energy, E_e. The value of α is somewhat uncertain. Burbidge (1959) uses $\alpha = 100$ on the assumption that the energy E_p is gradually transferred to secondary electrons produced by heavy-particle interactions. However, this process can be effective only in regions where the heavy-particle density is $\gtrsim 10^{-2}$ cm^{-3}.

The magnetic field energy E_m may be set equal to $H^2/8\pi$ times the volume occupied by the field. It has been customary in treatments such as this to assume that the magnetic field and the relativistic particles trapped in it are homogeneously distributed over the source volume. This may be the case, but it may also be that the source consists of tangled filaments and knots filling only a portion of the source volume. We let this portion be given by a filling factor ϕ. Then, if r is the radius of the emitting region, the magnetic field energy is

$$E_m = \phi \tfrac{4}{3}\pi r^3 \frac{H^2}{8\pi} = \phi \frac{H^2 r^3}{6}.$$

The total energy of the source (including the magnetic field and particles) is then given by

$$E_t = (1+\alpha)\, C' L H^{-3/2} + (\phi H^2 r^3)/6 .$$

As can be seen from the dependence of the two terms on H, the total energy will have a minimum not far from the value of H for which the particle and field energies are equal. The functional dependences of the minimum energy and of the field required for minimum energy are as follows:

$$E_{\min} \propto (1+\alpha)^{4/7} \phi^{3/7} L^{4/7} r^{9/7} ,$$

$$H(E_{\min}) \propto (1+\alpha)^{2/7} \phi^{-2/7} L^{2/7} r^{-6/7} .$$

It is seen that these quantities are most strongly dependent on the radius of the emitting region, which emphasizes the need for accurate brightness distributions in order to determine the physical characteristics of radio sources. The field is seen to be quite insensitive to changes in α or ϕ, the total energy only moderately so.

On the assumption that $\alpha = 100$, that $\phi = 1$, and that the field and particle energies are equal, the total energy requirements and the magnetic field have been calculated for each source, using the physical size obtained in Table 1, column 10. The results appear in the last two columns of Table 2. It is seen that the sources of small physical diameter, such as 3C 71 and the core of Virgo A, have magnetic fields near 10^{-4} oersted and comparatively low energy requirements of about 10^{56} ergs. The large, very luminous sources have energy requirements between 10^{60} and 10^{61} ergs.

As was mentioned earlier in this paper, the linear diameter of a source has been assumed to equal the product of the angular diameter and the distance. For the more distant sources, non-linear terms which depend on the choice of world model should be included in this calculation. As an example of the effect of this correction, the linear dimensions in Table 1 should be reduced by a factor of $(1+z)^{-1}$ for a steady-state universe or by $(1+z)^{-2}$ for a "$q_0 = +1$" universe. The correction for the source diameter will enter into the calculation of the energy, as will the correction for the source luminosity. The effects nearly cancel in the case of the steady-state universe, but for the case of $q_0 = +1$ the energy (E_t) of 3C 295 would be reduced by a factor of $(1+z)^{-18/7} \approx 0.38$.

VI. DISCUSSION

In three of the sources examined, the radio core component is double (Centaurus A, Virgo A, and probably Hydra A). It is tempting to suppose that these double cores represent new sources which have recently been formed in the nuclei of their respective galaxies and which may in time add to the radio halos already surrounding these galaxies. 3C 71 is even smaller in proportion to the galaxy and may also be such a "new" source. The observations further suggest that a radio source is formed in or near the nucleus of a galaxy; initially its diameter is of the order of 10^3 pc or less. As the two components of a source grow older, they move away from the galaxy; at least some of the double sources finally reach distances of about 150 kpc from the galaxy and diameters of about 100 kpc. The energy input for the radio source probably lasts for only a relatively short interval of time when the components are near the galaxy, and subsequently the source lives on its stored energy. Since a given electron radiates away its energy in a time shorter than the minimum source lifetime found below, the radiating electrons cannot form the main energy reservoir.

Using this hypothesis, one may derive from the sizes of the sources some information about their ages. In Hercules A we detect emission from a distance of at least 180 h^{-1} kpc from the galaxy; in 3C 219 a projected distance of 210 h^{-1} kpc is observed. In Centaurus A there is quite definitely emission at a distance of 5°.2, or about 360 kpc (Bolton and Clark 1960). An expansion velocity equal to the speed of light would give a minimum age for these objects of the order of 10^6 years. An expansion velocity typical of the velocity, v_A, of hydromagnetic wave propagation in a galactic halo—$v_A \sim 2 \times 10^8$ cm/sec, assuming $n \sim 10^{-3}$ cm^{-3} and $H \sim 3 \times 10^{-5}$ oersted—would give very much greater ages of the order of 10^8–10^9 years.

A rough upper limit on the source lifetimes may be obtained from total energy considerations. The total mass-energy of a large galaxy is $\sim 10^{66}$ ergs. It is difficult to imagine an efficiency greater than $\sim 10^{-4}$ for any process which might convert the mass of stars into clouds of high-energy particles and magnetic fields. This suggests that our minimum total energies for the stronger sources of $\sim 10^{61}$ ergs (Table 2) are also close to the maximum energies which the sources have ever possessed. Dividing 5×10^{60} ergs by a radiation rate of 10^{44} ergs/sec, we obtain an estimated remaining lifetime of $\sim 10^9$ years.

A very high total energy is required to explain the observed radio emission of the more luminous sources. For seven sources in Table 2, E_t is more than 10^{60} ergs. These energies could be reduced if the ratio of E_p to E_e were much smaller or if the filling factor were much less than unity. On the other hand, if the magnetic and particle energies are not approximately equal, then the total energy must be larger. An amount of energy equal to 10^{60} ergs is perhaps best visualized as the total mass energy of 5×10^5 stars of solar mass; all this energy must be available in the form of relativistic particles and magnetic-field energy. The energy problem in radio sources has recently been considered by Shklovskii (1960), Hoyle (1961), and Burbidge (1961). The variety of the mechanisms proposed is probably the best indication of the theoretical difficulties which this problem presents.

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