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OBSERVATIONS OF THE PERSEUS CLUSTER OF GALAXIES AT 3000 MC

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ABSTRACT

Radio observations at 3000 Mc with an angular resolution of 15.8 minutes of arc have been made in the vicinity of the Perseus cluster of galaxies. The brightness distribution obtained shows that there are two discrete sources in the region: Perseus A, usually identified with the peculiar galaxy NGC 1275, and a companion source of about four-tenths the intensity of Perseus A, possibly associated with NGC 1265, an elliptical galaxy about one magnitude fainter than NGC 1275 and probably a member of the Perseus cluster. There seems to be little evidence in the 3000 Mc data of an extended radio source associated with the cluster as a whole. Evidence is found from published flux measurements that the spectrum of Perseus A is much steeper at low than at high frequencies.

I. INTRODUCTION

One of the first attempts to observe radio emission from extragalactic objects was made by Brown and Hazard (1952) at a frequency of 158 Mc with a fixed 218-foot reflector. In addition to the successful detection of several bright, nearby spiral galaxies, one source* was found which coincided well in position with the Perseus cluster of galaxies at $\alpha = 03^{h}\ 16^{m}.2$, $\delta = +41^{\circ}\ 19'$ (1950). A comparison of the measured flux density of the source, approximately 60×10^{-26} w m^{-2}(c/s)$^{-1}$, with the measurements for Sb and Sc spiral galaxies indicated that one or more of the cluster members must be emitting radiation much more strongly than "normal" spirals. Brown and Hazard (1953) discussed the possibility (apparently suggested by Minkowski) that a significant fraction of the emission from the Perseus cluster might be contributed by the brightest member of the cluster, NGC 1275. This galaxy is known for its peculiar form and an optical spectrum showing strong and very broad emission lines. Observations by Baldwin and Elsmore (1954) were very important in this connection. These observations, made with a dual-spacing interferometer at 81.5 Mc, demonstrated that 75 per cent of the radiation from the Perseus cluster originates in a source of small angular dimensions corresponding well in position with NGC 1275. The remaining 25 per cent of the radiation seemed to come from a more extended source, presumably associated with the remaining galaxies

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* This source had also been observed by Ryle, Smith, and Elsmore (1950) at 81.5 Mc (RSE 03.02) and by Mills (1952) at 101 Mc (M 03 + 4).

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in the cluster.

The first mention of the double nature of the Perseus A source was made by Elsmore, Ryle, and Leslie (1959). It was found that 3C 84, the corresponding source in the third Cambridge catalogue (Edge, Shakeshaft, McAdam, Baldwin, and Archer 1959), was a combination of a fairly strong source at the position of NGC 1275, and a weaker companion source approximately 1.5 minutes of right ascension preceding. Both of these sources are shown in the aperture synthesis results of Scott, Ryle, and Hewish (1961). Finally, Leslie and Elsmore (1961) have reported that, in addition to these two sources of small angular size, there is also present an extended source with a diameter of 26 minutes of arc, possibly associated with the Perseus cluster. The flux densities given by Leslie and Elsmore are 41 x 10^{-26} and 15.5 x 10^{-26}w $m^{-2}(c/s)^{-1}$ for the two discrete sources, and 40 x 10^{-26}w $m^{-2}(c/s)^{-1}$ for the extended source.

In January, 1961, one of the present authors (Lynds) obtained a preliminary brightness distribution at 3000 Mc in the region of the Perseus cluster. These observations indicated the presence of the two discrete sources, the stronger source being coincident with NGC 1275 and the fainter showing fair position correspondence with NGC 1265, an elliptical galaxy near NGC 1275.

II. NEW OBSERVATIONS

In an attempt to detect and isolate the extended source in the vicinity of the Perseus cluster reported by Leslie and Elsmore, new observations at 3000 Mc were obtained during July and August, 1961, with the 85-foot Tatel telescope. The antenna pattern has nearly perfect axial symmetry and a width at half-power of approximately 15.8 minutes of arc. The receiver was a Ewen-Dae load-comparison radiometer, utilizing a traveling-wave tube front-end. The observations covered a region approximately nine minutes in right ascension by two degrees in declination centered on the Perseus cluster, and consisted of scans in declination at constant right ascension. The scanning positions were at 40-second intervals, corresponding to approximately one-half beamwidth. The receiver output was integrated over ten-second intervals while scanning, digitized, and punched on teletype tape. The ten-second integration times correspond to five minutes of arc in declination. All scans at each right ascension (approximately 28) were averaged and reduced with the aid of a Bendix G 15 computer. Calibration of the instrumental response in terms of flux density was achieved by observing the source 04N3A for which a flux density of 23.7 x 10^{-26}w $m^{-2}(c/s)^{-1}$ was adopted.

The averaged observations for the central seven scanning positions are given in Table 1. The values given are in degrees absolute on the instrumental antenna temperature system. Each value is the average response over five minutes of arc in declination, centered on the indicated declination. An internal probable error estimate is given for the observations in each of the scans. For comparison, the average of the calibration scans across 04N3A is also given in Table 1.

III. DISCUSSION

The observations given in Table 1 have been smoothed and a contour diagram drawn to represent the observed 3000 Mc brightness distribution in the vicinity of the Perseus

TABLE 1

THE AVERAGED OBSERVATIONS

	Antenna Temperature (°K) $\alpha(m) = 3^h\,13^m\,48^s\!.5 + (40^s)m$, $\delta(n) = +42°\,19'\!.7 + (5')n$ (1950)							
α(m) / δ(n)	α(0)	α(1)	α(2)	α(3)	α(4)	α(5)	α(6)	04N3A
δ(0)	-0.01	+0.01	0.00	0.00	+0.02	+0.01	-0.01	
δ(1)	-0.06	-0.02	-0.03	-0.01	+0.02	0.00	+0.06	
δ(2)	-0.07	-0.01	+0.06	+0.02	+0.04	-0.02	+0.03	
δ(3)	-0.02	+0.04	-0.02	-0.04	-0.02	-0.02	0.00	-0.02
δ(4)	0.00	+0.03	-0.01	-0.05	-0.02	0.00	-0.01	+0.01
δ(5)	0.00	-0.06	0.00	+0.03	-0.01	0.00	-0.02	+0.07
δ(6)	-0.02	+0.01	0.00	+0.06	-0.02	-0.01	-0.03	-0.06
δ(7)	-0.06	0.00	-0.02	-0.02	-0.01	+0.03	-0.01	-0.02
δ(8)	+0.06	+0.01	+0.03	-0.03	-0.01	-0.02	-0.01	+0.02
δ(9)	+0.06	+0.01	+0.01	0.00	+0.10	+0.02	+0.03	+0.36
δ (10)	+0.04	+0.01	+0.01	+0.02	+0.42	+0.18	+0.03	+1.25
δ (11)	+0.04	+0.04	+0.10	+0.40	+0.71	+0.33	+0.04	+2.08
δ (12)	+0.02	+0.02	+0.10	+0.43	+0.74	+0.36	+0.06	+2.16
δ (13)	+0.03	+0.02	+0.07	+0.31	+0.51	+0.20	+0.05	+1.27
δ (14)	+0.01	+0.02	+0.13	+0.12	+0.21	+0.06	+0.02	+0.40
δ (15)	+0.07	+0.12	+0.16	+0.03	+0.01	+0.01	0.00	+0.04
δ (16)	+0.10	+0.24	+0.32	+0.10	+0.01	+0.01	-0.02	+0.03
δ (17)	+0.07	+0.30	+0.29	+0.09	-0.03	+0.04	+0.03	+0.02
δ (18)	+0.09	+0.18	+0.18	+0.05	0.00	0.00	0.00	+0.03
δ (19)	+0.03	+0.03	+0.06	0.00	-0.03	0.00	-0.06	-0.02
δ (20)	+0.02	+0.01	0.00	0.00	0.00	+0.02	+0.01	-0.06
δ (21)	0.00	+0.03	+0.01	0.00	+0.03	-0.03	+0.04	0.00
δ (22)	0.00	-0.03	+0.02	-0.01	-0.02	-0.01	-0.01	
δ (23)	+0.01	-0.02	0.00	-0.01	+0.03	-0.05	-0.04	
δ (24)	-0.02	+0.01	-0.03	+0.03	+0.02	+0.03	-0.01	
p.e.	±0.024	±0.024	±0.020	±0.020	±0.019	±0.019	±0.020	±0.026

cluster. These contours are shown in Figure 1; the units of intensity are 0.1 °K antenna temperature. The main features shown by the distribution are two discrete sources separated by 32 minutes of arc, or approximately two beamwidths. The brighter source (Perseus A) we will designate as 3C 84a, and the fainter, 3C 84b. The source 3C 84a

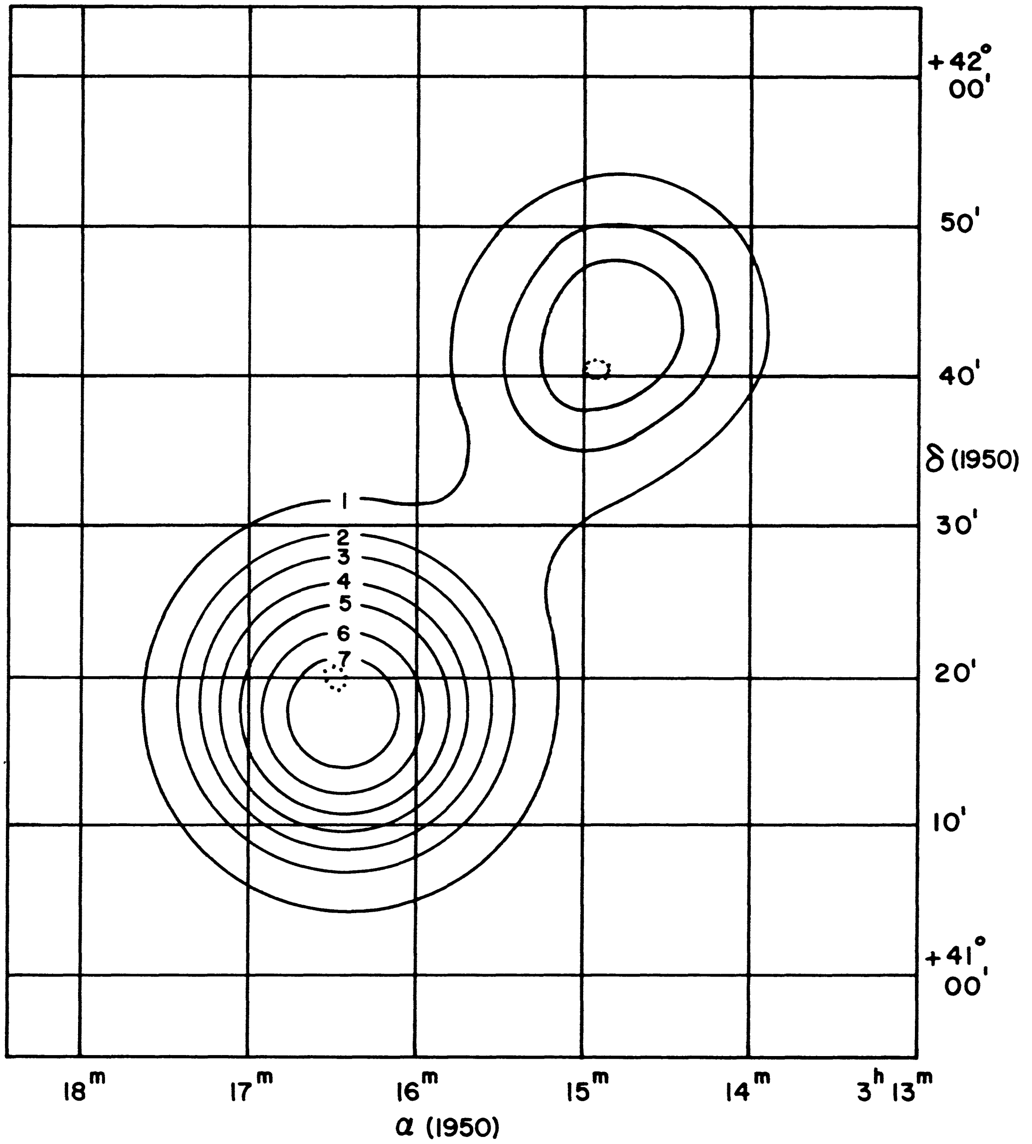

Figure 1.—Brightness distribution in the Perseus source (3C 84) at 3000 Mc. The distribution is uncorrected for antenna smoothing. The unit of intensity for the contours is 0.1 °K antenna temperature. The two dotted ellipses represent the size and position of NGC 1275 and NGC 1265.

shows little indication of broadening other than a possible asymmetry of about one minute of arc, in the sense that the lower contours seem to be displaced slightly toward the companion source. However, this effect is quite possibly a result of observational errors. The apparent distortion of the companion source must likewise be regarded as due to the inaccuracies of the measurements. On somewhat better footing is the evident "bridge" between the two sources. Because of the large separation between the two sources there should be little, if any, response at the midway point if the sources are, in reality, point sources. The material given by Leslie and Elsmore (1961) indicates a source diameter of one and two minutes of arc for the brighter and fainter components, respectively. Thus, the existence of a real "bridge" between the sources seems to be indicated by the present observations. This conclusion is admittedly quite tentative and needs confirmation because of its considerable bearing on the problem of optical identification of extragalactic sources, in general, and of double sources, in particular.

Except for the "bridge" there is very little evidence in the present material for the existence of the extended source reported by Leslie and Elsmore. The flux density of this source at 178 Mc was found to be essentially equal to that of 3C 84a. If this were also the case at 3000 Mc, the extended source should have produced a substantial broadening or distortion of the contours for the observed sources. Since this does not seem to be the case, we must conclude either that the spectrum of the extended source is very steep or that the observations are in error.

The positions and flux determinations for the two sources 3C 84a and 3C 84b are given in Table 2 along with similar measurements by Leslie and Elsmore. In addition, Table 2 contains the positions of NGC 1275 and NGC 1265. NGC 1275 is the generally accepted optical identification for Perseus A, and NGC 1265 would seem to be a likely identification for the companion source 3C 84b. The positions and approximate sizes of NGC 1275 and NGC 1265 have been indicated in Figure 1. The galaxy positions were measured from a Palomar 48-inch Sky Survey print of the region. It is seen that the optical position of NGC 1275 agrees with the two radio positions for 3C 84a within their uncertainties. In the case of the possible identification of NGC 1265 with 3C 84b, the right ascension agreement is satisfactory but there seems to be a discrepancy of about three minutes of arc in declination.

TABLE 2

RADIO AND OPTICAL POSITIONS AND FLUX DENSITIES

Name	α(1950)	p.e.	δ(1950)	p.e.	ν (Mc)	Flux Density*	p.e.
3C 84a	$3^{h}\ 16^{m}\ 25^{s}.7$	4^{s}	+41° 18'.1	1'	3000	8.4	0.4
3C 84a	3 16 28.6	1.5	+41 20.4	1.5	178	41	4
NGC 1275	3 16 27.6	1	+41 19.8	0.2			
3C 84b	3 14 53	5	+41 42.8	2	3000	3.7	0.4
3C 84b	3 14 54.2	1.5	+41 44.1	1.5	178	15.5	2
NGC 1265	3 14 54.6	1	+41 40.5	0.2			

* Units are 10^{-26}w m^{-2}(c/s)$^{-1}$.

However, because of the weakness of the source and consequent uncertainty in its position, this identification cannot be ruled out. It is obviously important that a better radio position of 3C 84b be obtained and that optical observations of NGC 1265 be made to investigate the possibility of peculiarities. Finally, radio observations of higher resolution and sensitivity should be made to establish or eliminate the possibility of the "bridge" between the two sources. As has been pointed out by Leslie and Elsmore (1961), the probability is very small that the sources 3C 84a and 3C 84b should occur with such a small angular separation, unless there is a physical relationship between the sources. Such a physical connection might be responsible for the "bridge" which, in turn, may have given rise to the observational evidence for the extended source reported by Leslie and Elsmore. As an alternative interpretation of the brightness distribution of the Perseus source shown in Figure 1, C. M. Wade has suggested (private conversation) that 3C 84b may be double. It seems likely that such a situation can explain the evidence for both the "bridge" and the extended component of Leslie and Elsmore and the poor position correspondence of 3C 84b with NGC 1265. Observational verification or rejection of these various possibilities is of obvious importance for the problem of source identification.

Because of the duplicity of Perseus A and possible additional complexities, it is difficult to interpret the flux measurements made at various frequencies with differing instruments and observing techniques. This is particularly true of interferometric observations made with only a few element-spacings. For certain element-spacings it is possible for the companion source to Perseus A to go unnoticed, yet still have an effect on the flux measurement of the brighter source. When observations are made with only two element-spacings it is even possible for a double source to be interpreted as a single source plus a "halo" or extended component. For these reasons it is necessary to exclude many of the published flux determinations of Perseus A in deriving the spectrum of the source. Measurements for which at least a limited interpretation seems possible are given in Table 3. The values given are ratios of 3C 84a flux density to Cassiopeia A flux density for the bright component of the Perseus source. Corrections for beam-width and beam-shape have been applied to the published fluxes and are based on the structure of the source shown by the present 3000 Mc observations, i. e., two point sources having an intensity ratio of 1.444:1 with a separation of 32 minutes of arc. No allowance was made for the possible extended source because of its unknown nature. In making these corrections it was assumed that the spectra of the two sources are the same. Although this assumption may break down at very high or low frequencies, the flux densities given in Table 2 indicate that it is not far wrong between 178 Mc and 3000 Mc. Most of the probable errors given in Table 3 have been derived from the error estimates given with the published flux densities. Among the flux ratios given in Table 3, the value for 81.5 Mc is the poorest, from an interpretive standpoint. This is the average of two interferometric determinations and the probable error given is simply a guess.

The flux ratios and corresponding frequencies given in Table 3 have been plotted in Figure 2 on logarithmic scales. The dashed curve is simply a free-hand curve to represent the values. The flux density of Cassiopeia A is known to obey, to a good approximation, a power law in frequency,

$$S_\nu \propto \nu^x,$$

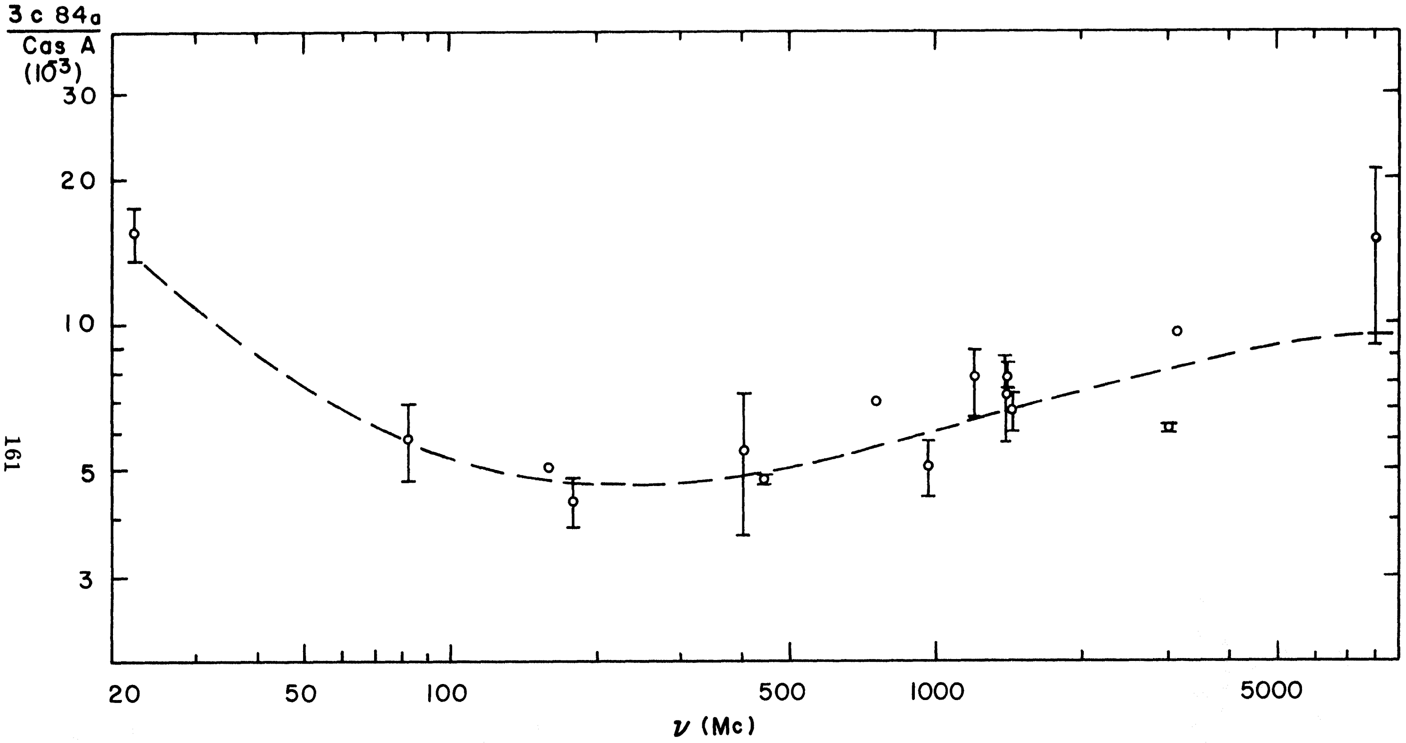

Figure 2.—Ratios of the flux density of 3C 84a to the flux density of Cassiopeia A as a function of frequency. The scales are logarithmic.

TABLE 3

RATIO OF FLUX DENSITIES
3C 84a/Cas A

ν (Mc)	$\frac{\text{3C 84a}}{\text{Cas A}}$ (10^{-3})	p.e.	Notes	ν (Mc)	$\frac{\text{3C 84a}}{\text{Cas A}}$ (10^{-3})	p.e.	Notes	ν (Mc)	$\frac{\text{3C 84a}}{\text{Cas A}}$ (10^{-3})	p.e.	Notes
22.2	15.6	2.0	1	440	4.81	0.1	6	1400	7.8	0.5	6
81.5	5.96	1.0	2	750	6.37	0.32	7	1422	6.63	0.62	10
158	5.11		3	960	5.10	0.67	8	3000	6.08	0.3	11
178	4.36	0.51	4	1200	7.7	1.2	6	3123	9.66		12
400	5.46	1.79	5	1390	7.1	1.42	9	8000	15	6	6

Notes to Table 3.

1) Burke and Franklin (1957).
2) Shakeshaft, Ryle, Baldwin, Elsmore, and Thomson (1955) and Baldwin and Elsmore (1954). The flux ratio given was derived from the average of the flux values given in the two references.
3) Brown and Hazard (1952, 1953).
4) Elsmore, Ryle, and Leslie (1959); Scott, Ryle, and Hewish (1961); and Leslie and Elsmore (1961). The flux ratio given is derived from the average of the flux densities quoted in the three references.
5) Seeger, Westerhout, and Conway (1957).
6) Heeschen (1961).
7) Heeschen and Meredith (1961).
8) Harris and Roberts (1960).
9) Westerhout (1958).
10) Goldstein (1961).
11) The flux ratio given is the result of averaging the present flux determination with that of Heeschen and Meredith (1961).
12) Kuzmin, Levchenko, Noskova, and Salomonovich (1960).

where x is known as the spectral index. Thus, the apparent curvature of the relation indicated in Figure 2 represents a spectral index changing with frequency. Taking Figure 2 at face value it would seem that at high frequencies the spectral index of 3C 84a is between -0.5 and -0.6, and at low frequencies, between -1.3 and -1.6. However, the uncertainties in the treatment of the published flux densities should be borne in mind. The best evidence for a varying spectral index is given by the 22.2 Mc measurement of Burke and Franklin (1957). It was recognized by these authors that the spectrum of the source was peculiar and no reason has since appeared to cast doubt on the accuracy of their determination (Burke 1961). The peculiar spectrum of the Perseus source has been studied by D. S. Heeschen and will be discussed by him in a forthcoming publication along with the spectra of many other sources.

IV. CONCLUSIONS

In making identifications of radio sources with optical galaxies we have at the present time only two criteria: good position correspondence and the existence of some type of peculiarity in the galaxy to be associated with a source. The first of these criteria is generally considered as a necessary and, when fulfilled to a high degree, sufficient condition in making an identification. The second criterion usually only lends confirmation when found to be satisfied in any of a wide variety of ways. These considerations hold for relatively uncomplicated discrete sources and are at best somewhat uncertain. For complex or double sources the criterion of position correspondence may be without meaning, or at least its nature difficult to establish. In such cases optical peculiarities among the candidates for identification assume a more important role. Taking double sources as an example, we may state the proposition, adopted by some investigators, that the optical identification should show a good position correspondence with the center of gravity of the two radio components. As reasonable as this presumption may be, there would seem to be only a small amount of evidence in support of it. Consider the better known double sources with accepted extragalactic identifications: Fornax A, Cygnus A, and Centaurus A (after subtraction of the central component). The center of gravity of the components of the Fornax A source shows good position correspondence with the peculiar galaxy NGC 1316 (absorption patches) (Wade 1961). A similar situation would seem to hold for the optical identification of Cygnus A, although in this case the absolute accuracy is not of certain adequacy. In the case of the double subsystem in the Centaurus A source there is not good position correspondence between the center of gravity of the radio emission and NGC 5128, the accepted identification, although the central source of the system, itself finely double, does fall within the boundaries of the galaxy (Wade 1959; Twiss, Carter, and Little 1960). All of these complex sources would be agreed upon as being physical systems. If, as seems possible, the double source in Perseus is also a physical system, and not just an improbable projection of two unrelated discrete sources, then we have a case where the most likely optical identification falls a considerable distance from the center of gravity of the radio emission and, in fact, coincides well with the brighter component of the source. When we consider double sources with substantially unequal components or discrete with "halos" (Moffet and Maltby 1961), it is possible that the use of accurate position determinations in making identifications may become extremely difficult. Even for simple discrete sources, there may be some question as to whether exact position coincidence is a necessary consequence of a physical association between the source and a galaxy. It would seem that an understanding of the physical conditions giving rise to abnormally strong radio emission in a galaxy will be invaluable in demonstrating a physical connection between radio sources and individual galaxies. One of the best hopes in gaining such an understanding is through extensive and comprehensive optical observations of the best established abnormal radio galaxies.

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