ON THE IDENTIFICATION OF EXTRAGALACTIC RADIO SOURCES

By B. Y. Mills*

[*Manuscript received March 22, 1960*]

Summary

Identifications of radio sources with galaxies and clusters of galaxies have been sought systematically in a limited region of the sky. The optical data have been taken principally from the National Geographic Society–Palomar Observatory Sky Atlas and a catalogue of clusters of galaxies prepared by Abell (1958) from the same Atlas. The radio data are taken from results obtained with the Sydney cross-type radio telescope, supplemented at times with additional information from a recent Cambridge Catalogue (3C). A total of 46 possible identifications with galaxies are listed and 55 possible identifications with clusters of galaxies, the great majority of which are new. Most of these galaxies are double systems, but no other common features could be recognized: it seems probable that many galaxies of completely normal appearance are very strong radio emitters. The possible nature of the double galaxies is discussed briefly and attention is drawn to a corresponding duplicity in the radio brightness distribution observed in some strong radio sources. In many cases the emission from clusters appears to be associated with a single galaxy or pair of galaxies in the cluster; evidence for the existence of radiation of intergalactic origin is inconclusive. A selection of the possible galaxy identifications has been used to derive a provisional radio luminosity function; it appears probable that there is no distinct class of "radio galaxies", but all radio luminosities appear to be represented, the numbers of radio sources in a given volume of space falling rapidly with increasing luminosity. A radio luminosity function of the form derived is capable of accounting for a substantial number of the radio sources of small size observed at high galactic latitudes; the remainder could be accommodated by the uncertainty in the data. It is found that, at the levels to which source counts can currently be taken, cosmological effects are likely to be small, although the most distant sources are markedly affected.

I. Introduction

To understand the physical significance of radio astronomical observations it is necessary to identify the types of objects in which the radiation originates. A number of such objects are known; at galactic distances these include hydrogen emission nebulae, supernova remnants, and the whole Galaxy itself; extragalactic objects include other spiral and irregular galaxies radiating in much the same way as our own, large clusters of galaxies, and very rare types of galaxies radiating many orders of magnitude more than the average. However, the great majority of detectable radio sources remain unidentified.

The galactic radio sources are rare objects concentrated very close to the plane; they may be identified only when there is fortuitously a "window" through the general dust clouds in their direction, or else when they are very close. A high proportion of identifications is therefore not expected. At high galactic latitudes, however, obscuration is low and the lack of identification must be related to the types of objects causing the emission; if these are galaxies they must be very distant.

* Division of Radiophysics, C.S.I.R.O., University Grounds, Chippendale, N.S.W.; present address: School of Physics, University of Sydney.

The need is evident for a systematic comparison of a large and homogeneous sample of radio sources with an equally homogeneous sample of galaxies. In the present investigation such a comparison has been made and many new possible identifications of "radio galaxies" and clusters found. It has also proved feasible to take the first steps in the derivation of a radio luminosity function for galaxies which is consistent with the existing observational results.

II. Observational Data

The radio data have been taken principally from a recent catalogue of sources between declinations $+10°$ and $-20°$ observed with the Sydney cross-type radio telescope at a wavelength of $3 \cdot 5$ m (Mills, Slee, and Hill 1958). For the optical data, the basic source has been the original plates of the National Geographical Society–Palomar Observatory Sky Atlas in the same region. These have been supplemented by additional radio data at more southerly declinations and a recent Cambridge catalogue of radio sources (3C) which has been made available in advance of publication;* also many plates taken with the larger telescopes of the Mount Wilson and Palomar Observatories have been examined.

The basic catalogue of radio sources includes 1159 within the declination limits of $+10°$ and $-20°$. The Cambridge 3C catalogue used for supplementary information includes 112 sources in the same area, of which about 85 can be recognized in the Sydney catalogue. The great majority of the 3C sources which could not be recognized were weak sources close to the galactic plane where the situation is confused by the existence of a high concentration of extended non-thermal and thermal sources, so that different types of instruments might be expected to yield different results. When a source was listed in both catalogues, it was found that the Right Ascension listed in the Sydney catalogue could usually be improved substantially by use of the 3C data. This possibility arose because the latter catalogue was prepared using an interferometer which gave quite precise values for the time of transit across a fictitious meridian inclined at a few degrees to the true meridian, but subject to possible lobe ambiguities. Once the correct lobe had been identified (about 30 per cent. required lobe shifts to bring them into coincidence with the Sydney position) and the Sydney declination adopted (because very large apparent errors in some of the 3C declinations caused uncertainty as to how they should be applied), the most probable Right Ascension was then determined giving the 3C data some three or four times the weight of the Sydney values. For the stronger sources it is estimated that the probable error in Right Ascension due to this procedure is of the order of $\frac{1}{2}$ min of arc, compared with an average probable error of about 3 min in declination. These errors would be roughly doubled for the weaker sources included in the 3C catalogue. When the 3C data are not available, the accuracy in Right Ascension is only slightly better than in declination.

The angular sizes of radio sources having possible identifications were also measured at the same wavelength when this was feasible. The instrument

* This catalogue has now been published with some slight modifications (Edge *et al.* 1959).

used is described elsewhere (Goddard, Watkinson, and Mills 1960); briefly, it consists of two interferometers of identical sensitivity but different spacings between aerials, one of 30λ and the other 3000λ. By measuring the ratio of responses on each spacing a crude estimate of the angular size of a radio source is possible. The sizes quoted later in this paper were derived on the assumption that the brightness distribution across a radio source is circularly symmetric and has a Gaussian distribution. On this assumption the angle between half-brightness points is given by

$$\theta_0 \approx 37 \cdot 4(\ln X)^{\frac{1}{2}} \text{ seconds of arc,}$$

where X is the ratio, response at 30λ/response at 3000λ. When X is large, greater than 3 or 4, fine structure in the distribution is likely to dominate and lead to a low estimate for the size. As X approaches unity, measurement errors become important and limit the size which can be measured to something greater than 10–30 sec of arc, depending on the intensity of the source. Because the sensitivity of the angular size interferometer is less than that of the radio telescope used in preparing the original catalogue, not all the selected radio sources could be measured.

Finally, comparisons were made between the radio sources and a very homogeneous collection of data on clusters of galaxies prepared by Abell (1958). Abell's catalogue, being prepared from the plates of the Palomar Sky Survey, is based on the same material as the other optical data used.

III. Analysis of the Data

A preliminary inspection of the Sky Survey plates showed the futility of any attempt to identify all the radio sources. The positional uncertainties of the weakest sources are so large that numerous galaxies are contained within their limits, and one can only consider seriously coincidences with the very bright galaxies which had been investigated earlier (Mills, Slee, and Hill 1958). Also, near the galactic plane, the obscuration is so heavy and the star density so high that the search appeared hopeless. Accordingly, only a limited sample of sources was inspected; this sample was chosen from the Sydney catalogue as follows.

(i) All Class II sources (i.e. sources having $|b| > 12\frac{1}{2}°$) with flux densities 2×10^{-25} Wm^{-2} (c/s)$^{-1}$ or higher. The catalogue is reasonably complete in this category.

(ii) Fainter sources, or sources with lower latitude, recognized in the 3C catalogue.

(iii) All sources, not included above, in two areas at high latitudes selected because of their low radio background emission and freedom from any obvious clustering of bright galaxies. These areas are defined by the Sky Survey plates centred on $09^h\ 36^m$ to $11^h\ 12^m$, $-18°$ to $0°$; and $23^h\ 12^m$ to $23^h\ 36^m$, $-18°$ to $0°$.

A total of about 400 positions was examined, made up of about 230 in category (i), 20 in category (ii), and the remaining 150 in category (iii).

Initially, the source positions were plotted approximately on the Sky Survey prints using offsets from catalogued stars. The area within three probable errors of the position was searched for the presence of single galaxies brighter than $m_p \approx 16$, or double systems brighter than about magnitude 19. All such coincidences were then investigated more closely on the original plates. Here positions were plotted to an accuracy of about $\frac{1}{2}$ min of arc and coincidences taken to be significant only when the discordance was less than two probable errors (unless the object showed great peculiarity). The fainter sources in category (iii) received slightly different treatment as the listed errors were ignored and coincidences sought within 10 min of arc of their positions: only galaxies showing some peculiarity, or double systems were noted.

A total of 46 coincidences were considered to be worth recording. The angular sizes of 38 of these have subsequently been measured.

In categories (i) and (ii) (containing 250 sources) there were 39 coincidences, of which 19 were with single galaxies and 20 with apparently double or multiple systems. To check the possibility of chance coincidences, a number of randomly selected positions was examined. Out of 200 positions, each with an associated area of 50 square minutes (corresponding roughly to the mean positional uncertainties), 4 coincidences were found with single galaxies of magnitude 16 or brighter, and 2 with very faint double systems of about magnitude 19. The number of chance coincidences with galaxies brighter than magnitude 16 to be expected from the data of Hubble (1936) is 6, in agreement with the above result. Thus it appears safe to conclude that the majority of coincidences, particularly with the double galaxies, are significant. The angular size data have proved very useful in making individual decisions: they also indicate that a very high proportion of the double galaxies are likely to be real identifications.

Among the radio sources in category (iii), seven coincidences were found, comprising six double galaxies and one peculiar single system. On the basis of the above statistical tests, about half a dozen coincidences might be expected with faint double systems due to chance, so that little weight can be given to the coincidences.

A different procedure has been adopted in making comparisons with Abell's catalogue of clusters. In this case the clusters are often very extended objects so that precise positions are of little use. Accordingly, all the 1159 radio sources in the Sydney catalogue have been compared with the 877 clusters listed in the area of the radio catalogue. Coincidences have been noted for positions agreeing within 1 min in Right Ascension and 20 min of arc in declination, a compromise based on the desire to exclude as many chance coincidences as possible without eliminating many real identifications. A total of 55 coincidences were noted. The chance coincidences were estimated by comparing the radio positions of 1950 epoch with the cluster positions of 1855 epoch given in Abell's catalogue. These totalled 16 so that the majority of the 55 coincidences are likely to be real identifications.

IV. Possible Identifications

The data relating to observed coincidences have been collected in Tables 1, 2, and 3. Tables 1 and 2 include coincidences observed with single or double galaxies during examination of the Sky Survey plates, and Table 3, the

TABLE 1

COINCIDENCES BETWEEN RADIO SOURCES AND GALAXIES IN WHICH THE ANGULAR SIZE MEASUREMENT IS CONSISTENT WITH AN IDENTIFICATION

When bracketed the angular size measurement is doubtful. Sources marked with an asterisk are included in the 3C catalogue

Radio Source			Galaxy Position (1950)		Flux Densities (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Angular Size ″	Notes
Ref. No.	Adopted Position (1950)						
	R.A. h m s	Dec. ° ′	R.A. h m s	Dec. ° ′			
00+02*	0 10 00^{4}	+0 37^{5}	0 10 03	+0 34	20	(∼30)	A faint galaxy which appears double with the 200 in. telescope.† The magnitude of the combined systems is 18: giving $m_{1\cdot 9}-m_p=-9$:. The size is admissible for an identification but needs checking. Another somewhat peculiar galaxy is at $0^h\ 10^m\ 08^s$, $+0°\ 24'$, but the position is too discordant
00—04	0 17 48^{12}	—02 51^{4}	0 17 49	—02 56	23	(⩾30)	A faint double galaxy, one component has magnitude 17: the other 19:. The size is admissible but needs checking. $m_{1\cdot 9}-m_p=-8$. A normal Sc galaxy of magnitude 16 is at $0^h\ 17^m\ 42^s$, $-02°\ 56'$
00—18	0 16 12^{12}	—10 46^{5}	0 16 20	—10 39	23	(>30)	A distorted Sc ($m_p=14\frac{1}{2}$) with an early type companion ($m_p=16$) about 1′ south. The size needs checking but at present appears to support the identification. $m_{1\cdot 9}-m_p=-5\frac{1}{2}$
00—015*	0 51 39^{3}	—3 42^{4}	0 51 39	—3 43	23	⩾35	A close double galaxy with some distortion in the outer parts. The combined magnitude is about 17. This appears a very likely identification with $m_{1\cdot 9}-m_p=-8$
01+04	01 23 06^{18}	+01 22^{5}	01 22 57	+01 30	20	>30	NGC533 ($m_p=12\cdot 5$) a normal E3 galaxy. The size measurement is consistent with the identification. $m_{1\cdot 9}-m_p=-3\cdot 4$

01—05*	01 23.33^2	—01 35^2	01 23 28	—01 36	88	~45	NGC545/547. A pair of elliptical galaxies each of magnitude 13, giving $m_{1\cdot9}-m_p=-5\cdot7$. The position given is that of the centroid of the system. The radio position appears closer to that of NGC547 and the size measurement indicates that the whole system is not radiating uniformly. The galaxies are in a loose cluster, A194
02—110	02 35 24^6	—19 43^3	02 35 18	—19 41	44	~30	A faint double galaxy ($m_p=18$:) or a close conjunction of a star and galaxy. The angular size is consistent with the identification and a photograph with the 200 in. telescope would be useful to decide on the nature of the object. The galaxy appears to be a member of a distant cluster, A367. We have $m_{1\cdot9}-m_p\approx-10$
02—014*	02 40 06^4	—00 09^3	02 40 06	—00 14	35	(>30)	NGC1068, a well-known identification and one of the class of galaxies with strong and broad emission lines in the nucleus. The angular size needs checking. Taking $m_p=9\cdot6$, we have $m_{1\cdot9}-m_p=-1\cdot1$
02+010*	02 55 07^4	+05 53^4	02 55 02	+05 50	51	(~40)	A pair of elliptical galaxies each with $m_p=15\frac{1}{2}$, separation about 15″ NS. Using the combined magnitudes we have $m_{1\cdot9}-m_p=-7$. The galaxies are in a loose cluster and an angular size of 5′ is given in the 3C catalogue. Possibly there is some radiation from the cluster as a whole, or another member of the cluster
02+011*	02 59 02^4	+01 35^5	02 59 02	+01 43	27	(>30)	A close double galaxy of about magnitude 17, giving $m_{1\cdot9}-m_p=-8$. The declination agreement is not particularly good and needs checking but is acceptable. The size measurement is consistent but also needs checking. The double galaxy may be associated with the cluster A409
03+03*	03 05 50^3	+03 50^5	03 05 48	+03 56	34	>40	NGC1218, an So of normal appearance and magnitude 15, giving $m_{1\cdot9}-m_p=-6\frac{1}{2}$. The angular size is consistent. There is an interesting double galaxy about 12^s following, but this appears too far away

† Minkowski suggests that this object is a close conjunction of a foreground star and a single galaxy.

TABLE 1 (*Continued*)

Ref. No.	Radio Source: Adopted Position (1950) R.A. h m s	Radio Source: Adopted Position (1950) Dec. ° ′	Galaxy Position (1950) R.A. h m s	Galaxy Position (1950) Dec. ° ′	Flux Densities (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Angular Size ″	Notes
03—03*	03 31 44^3	—01 25^4	03 31 45	—01 28	64	35	A very faint double galaxy ($m_p \approx 19$–20). It could not be considered but for the angular size measurement. However, there are some 18 magnitude galaxies of normal appearance quite close so that the identification is uncertain. We have $m_{1\cdot 9} - m_p \approx -11$
05—*11**	05 02 37^6	—10 13^5	05 02 31	—10 19	20	>30	A rather interesting Sb of magnitude about $15\frac{1}{2}$. It displays heavy obscuration in the spiral arms and has strong λ3727 emission, but otherwise a normal spectrum. We have $m_{1\cdot 9} - m_p = -6\frac{1}{2}$
05+02*	05 10 55^3	+01 02^6	05 10 56	+01 08	38	(>30)	An Sab galaxy of magnitude about 16, giving $m_{1\cdot 9} - m_p = -7\frac{1}{2}$. There is a superimposed star suggesting a double galaxy on the Sky Survey plates. However, with the 200 in. telescope the star is separated and a heavy absorption lane is visible around the nucleus. The angular size is consistent with the identification, but needs checking
08+03*	08 19 54^4	+06 07^4	08 19 50	+05 55	125 (60)	~30 + extended component	A double S, each component having a magnitude of $17\frac{1}{2}$. Taking the combined magnitudes we have $m_{1\cdot 9} - m_p = -8\frac{1}{2}$. An identification of the galaxy pair with the small source appears quite possible. The discrepancy in declination could then be explained by radiation from the extended source, which might be associated with a coincident loose cluster of galaxies

09—*14**	09 15 43^{2}	—11 52^{2}	09 15 42	—11 53	690	~50	An earlier identification which now appears practically certain. A very close double E galaxy with a combined magnitude of 15·9 in the cluster A780. The galaxy shows some emission lines, λ3727, the nebulium lines and Hβ. $m_{1\cdot9}—m_p=—10\frac{1}{2}$
10—*018*	10 46 18^{12}	—02 33^{5}	10 46 30	—02 36	20	(~30)	A double galaxy, or else perhaps a galaxy with superimposed star each of about magnitude 17. Since the positional agreement is not particularly good and the nature of the object in doubt, this coincidence cannot be given much weight. The angular size also needs checking. $m_{1\cdot9}—m_p=—7$
11—*08*	11 16 54^{12}	—02 46^{3}	11 16 34	—02 48	31	>30	A pair of faint galaxies both of magnitude about 18 separated by about 10″ arc. The size is consistent and the agreement in R.A. poor but acceptable. There is another pair about 2 magnitudes brighter separated by ½′ arc at $11^h\ 16^m\ 51^s$, —2° 49′. The separation is rather large but these could also be the radio source. There are no other likely candidates nearby. The selected pair have $m_{1\cdot9}—m_p=—7\frac{1}{2}$
12+*04*	12 14 48^{12}	+04 00^{6}	12 14 36	+03 58	30	>40	NGC4234, an Irregular galaxy of magnitude 12·4. This is one of Haro's blue galaxies. The spectrum shows λ3727 in emission but has no other peculiarities. The size is consistent with an identification. $m_{1\cdot9}—m_p=—3\cdot7$
12+*05**	12 16 51^{4}	+05 59^{5}	12 16 50	+06 07	100	~55	NGC4261, an apparently normal E2 of $m_p=10\cdot9$, giving $m_{1\cdot9}—m_p=—3\cdot5$. The declination agreement is rather poor but acceptable. NGC4264, which appears somewhat peculiar, is 5′ further north, too far for serious consideration
12—*118**	12 52 03^{6}	—12 19^{4}	12 52 00	—12 18	53	>50	NGC4782/4783, a pair of very similar So galaxies, each of magnitude 12·7 and about 1′ arc apart in a common envelope. This appears to be a very likely identification with $m_{1\cdot9}—m_p=—3\cdot8$. The galaxy position is that of the centroid of the double system

G

TABLE 1 (*Continued*)

Ref. No.	Radio Source: Adopted Position (1950) R.A. h m s	Radio Source: Adopted Position (1950) Dec. ° ′	Galaxy Position (1950) R.A. h m s	Galaxy Position (1950) Dec. ° ′	Flux Densities (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Angular Size ″	Notes
14—*019*	14 55 30^{18}	—00 54^{7}	14 55 48	—00 54	19	(>30)	A normal SBc galaxy of magnitude 11·7, giving $m_{1\cdot9}—m_p=—2\cdot5$. There are no other galaxies in the vicinity likely to have large radio size. However, the size needs to be checked
15+*05**	15 14 17^{5}	+07 11^{6}	15 14 20	+07 12	140	~40	Two Eo galaxies, of magnitudes $15\frac{1}{2}$ and 16, separated by 1′ arc in a small cluster. The position and size fit the brighter member better. Taking the combined magnitudes, we have $m_{1\cdot9}—m_p=—8$
16+*010**	16 48 44^{4}	+05 04^{2}	16 48 49	+05 02	890	~55	The radio source is Hercules A, which previously had been identified with the double galaxy noted of magnitude $17\frac{1}{2}$. However, this identification has now been queried and is possibly incorrect: it is discussed in the text. $m_{1\cdot9}—m_p=—12\frac{1}{2}$. The size given in 3C is 2′·3: there is undoubtedly fine structure in a quite large source
17—*23*	17 09 24^{12}	—23 18^{5}	17 09 25	—23 15	45	⩾40	A very obscured field; but a cluster of galaxies is visible, the brightest member being close to the radio position as noted. The apparent magnitude is 17 but because of the obscuration it is undoubtedly very much brighter. $m_{1\cdot9}—m_p=—9$

17—06*	17 18 00^{3}	—00 55^{3}	17 17 59	—00 54	475	~50	Again a very obscured field with the brightest member of a cluster close to the radio position. The apparent magnitude is 17, but it is intrinsically very much brighter. $m_{1\cdot 9}-m_p \geqslant -11$. The 3C catalogue gives the size as 3′·5, which would be consistent with the identification and with our measurement assuming the existence of some fine detail in the brightness distribution. Boischot gives 6′, which is difficult to reconcile, but perhaps there is some additional radiation from the cluster. In the Sydney catalogue the possible presence of an extended source is noted
20+*010**	20 45 46^{4}	+06 57^{7}	20 45 41	+06 50	22	(<30)	A pair of very red galaxies each of magnitude 18½ and with separation 5″. The object appears interesting and the size is admissible although uncertain. The galaxies appear to be associated with a very distant cluster. $m_{1\cdot 9}-m_p=-9$
21—*21*	21 04 36^{12}	—25 36^{3}	21 04 32	—25 38	50:	⩾50	A close pair of elliptical galaxies, each of magnitude 16½, in a small cluster containing two other early type pairs. Using the combined magnitude, we have $m_{1\cdot 9}-m_p=-7$
22—*09**	22 21 23^{5}	—02 18^{3}	22 21 29	—02 23	60	~45	A rather peculiar galaxy of magnitude 17. With the 200 in. telescope it appears as an edge-on spiral with dense nucleus and a bright concentration on one edge. The overall size is nearly ½′, which is consistent with the radio size, but the positional agreement is not particularly good. $m_{1\cdot 9}-m_p=-9$
23+*03**	23 09 20^{4}	+09 16^{8}	23 09 19	+09 16	*51* (29)	>40	An apparently normal So of magnitude 15½ in a loose cluster (Pegasus II). The fact that the source is observable with the Cambridge interferometer indicates that a source of small size must be involved. The observations are consistent with radiation from the single galaxy noted plus radiation from the cluster. $m_{1\cdot 9}-m_p=-7$:

TABLE 2

COINCIDENCES BETWEEN RADIO SOURCES AND GALAXIES IN WHICH NO ANGULAR SIZE DATA ARE AVAILABLE OR IN WHICH THE SIZE DOES NOT SUPPORT THE IDENTIFICATION

Ref. No.	Radio Source Adopted Position (1950)		Galaxy Position (1950)		Flux Densities (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Angular Size ″	Notes
	R.A. h m s	Dec. ° ′	R.A. h m s	Dec. ° ′			
00—*06*	00 21 30^{24}	—08 14^{6}	00 21 28	—08 19	24	~25	An So galaxy of normal appearance and magnitude 16:. The angular size is rather small but not impossible. However, there are several fainter galaxies within the area of uncertainty which would fit the size better
00—*017**	00 54 24^{6}	—01 39^{2}			*90* (72)	>45	This source is probably a blend of a moderately small source and an extended source. One interpretation of the data would give radiation in almost equal amounts from a small cluster (A119) and an Eo galaxy of normal appearance and magnitude 16:
01—*06**	01 29 00^{8}	—07 03^{6}	01 28 52	—07 07	19	~30	NGC584. A normal E3 galaxy of magnitude 11·2. The angular size appears too small for this identification. Probably the coincidence is a chance one
02—*15**	02 13 10^{4}	—13 19^{3}	02 13 01	—13 17	42	~20	An apparently normal Sc of magnitude 15½. The size appears to be rather too small and, since there are numerous very faint galaxies within the position uncertainty, probably the rather poor positional coincidence is the result of chance
04+*014**	04 58 15^{6}	+01 24^{6}	04 58 20	+01 18	15	—	An early type spiral of magnitude 16½ which displays very heavy absorption in the spiral arms. The flux density is too low for a measurement of size

08—*02**	08 03 09^{4}	—00 30^{6}	08 03 06	—00 49	15	—	A very interesting multiple galaxy with at least 2 and perhaps 3 components. The brightest has magnitude 16. The declination is rather far off, but the 3C declination is off by an equal amount on the other side: examination of the original Sydney records reveals some ambiguity due to confusion effects and the galaxy position is admissible. The system possibly belongs to a distant cluster, A623, and radiation from this may be causing difficulties. An angular size measurement would be very desirable but the flux is too low
09—*16*	09 31 24^{18}	—16 47^{6}	09 31 29	—16 46	13	—	An Sb showing either a double nucleus, or a star superimposed on the nucleus. A photograph with the 200 in. telescope might disclose the nature of the object.
09—1*10*	09 42 42^{18}	—19 33^{6}	09 42 36	—19 30	12	—	An interesting pair of spirals, each of magnitude $16\frac{1}{2}$: and about $0'\cdot 8$ apart. Similar galaxies are not radio sources and this coincidence may be chance
09—1*14*	09 54 00^{18}	—13 36^{6}	09 54 18	—13 31	14	—	The brightest galaxy in the vicinity, of magnitude 15, it has a peculiar concentration at one edge. However, there are several fainter galaxies which cannot be eliminated
10—0*3*	10 08 06^{18}	—07 25^{6}	10 08 18	—07 37	17	(∼40)	A close pair of galaxies each of magnitude 17. The declination is rather far off but admissible. There are several fainter galaxies in the vicinity, however, and the size measurement is rather uncertain
10—0*10*	10 25 24^{18}	—07 20^{6}	10 24 40	—07 18	10	—	A close pair of galaxies each of magnitude 18. The agreement in R.A. is poor but admissible
21+0*10*	21 49 36^{24}	+07 52^{8}	21 49 45	+08 00	23	(<30)	A very close double galaxy with a combined magnitude of 17. There are several fainter galaxies nearby. The size needs checking but at present suggests an association with one of the fainter galaxies

TABLE 2 (*Continued*)

Ref. No.	Radio Source: Adopted Position (1950) R.A. h m s	Dec. ° ′	Galaxy Position (1950) R.A. h m s	Dec. ° ′	Flux Densities (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Angular Size ″	Notes
22—17*	22 11 55^{5}	—17 11^{4}	22 11 45	—17 14	127	~35	A spiral of normal appearance and magnitude 16, perhaps associated with a small cluster. The size is somewhat low but acceptable; however, there are several fainter galaxies within the limits of uncertainty which fit the size better
23—0*8*	23 15 36^{18}	—02 29^{7}	23 16 13	—02 36	9·8	—	A double galaxy of combined magnitude 18: and separation 5″. The position agreement is rather poor but acceptable
23—1*12*	23 22 36^{12}	—12 29^{5}	23 22 43	—12 25	30	<20	An So with a very bright nucleus and magnitude = 16. The small size counts against the identification and, as there are numerous galaxies of magnitude 19–20 within the positional uncertainty, the coincidence is probably chance
23—0*15*	23 38 00^{18}	—00 08^{6}	23 38 25	—00 11	11	—	A rather distorted double galaxy of late type and combined magnitude about 17. This is an interesting-looking object but the size of the source cannot be measured

Table 3

COINCIDENCES BETWEEN RADIO SOURCES AND THE CLUSTERS OF GALAXIES IN ABELL'S CATALOGUE

The photographic magnitude given is that of the tenth brightest cluster member

Radio Source				Cluster			
Ref. No.	Position (1950) R.A. h m	Position (1950) Dec. ° ′	Flux Density (10^{-26} Wm^{-2} (c/s)$^{-1}$)	Ref. No.	Position (1950) R.A. h m	Position (1950) Dec. ° ′	m_p
00—*14*	00 05·6^{3}	—19 58^{6}	17	2	00 58·8	—19 54	17·3
00+*03*	00 14·2^{3}	+06 48^{7}	12	16	00 14·1	+06 30	17·0
00—*111*	00 25·3^{4}	—13 10^{7}	13	36	00 25·1	—13 03	17·6
00+*07*	00 30·8^{3}	+05 53^{5}	25	55	00 31·3	+06 05	17·2
00—*017*	00 54·5^{1}	—01 39^{2}	90 (72)	119†	00 53·8	—01 31	15·0
01—*14*	01 08·2^{4}	—14 33^{6}	16	157	01 08·5	—14 40	16·9
01—*05*	01 23·5^{1}	—01 35^{2}	88	194†	01 23·0	—01 45	13·9
01—*113*	01 36·9^{4}	—17 49^{6}	10	235	01 37·7	—17 40	17·5
02—*09*	02 29·4^{3}	—04 55^{5}	12	362	02 29·1	—05 05	17·7
02+*010*	02 55·1^{1}	+05 53^{4}	51	400†	02 54·9	+06 01	13·9
03—*11*	03 03·5^{3}	—12 21^{5}	18	415	03 03·4	—12 14	16·3
03—*12*	03 05·4^{4}	—16 44^{6}	17	416	03 04·9	—16 55	17·7
04—*05*	04 09·5^{3}	—01 50^{5}	15	477	04 09·6	—02 00	17·5
04—*112*	04 32·0^{2}	—13 26^{5}	38	496	04 31·3	—13 21	15·3
04—*016*	04 46·8^{3}	—09 55^{5}	16	513	04 45·8	—09 48	17·5
04+*011*	04 51·5^{4}	—02 33^{6}	10	520	04 51·6	+02 53	17·4
04+*013*	04 56·3^{3}	+05 20^{8}	10	526	04 57·1	+05 24	16·4
05—*14*	05 13·0^{3}	—15 56^{8}	11	538	05 12·9	—15 45	17·4
08—*02*	08 03·1^{3}	—00 30^{6}	15	623†	08 03·1	—00 49	16·9
08+*010*	08 55·0^{4}	+03 36^{8}	9·0	732	08 55·2	+03 22	17·7
09—*02*	09 06·5^{3}	—09 38^{6}	17	754	09 06·4	—09 27	15·2
09—*14*	09 15·7^{1}	—11 53^{2}	690	780†	09 16·0	—12 04	16·6
09+*05*	09 41·8^{3}	+09 57^{7}	32	862	09 42·1	+09 44	17·7
09+*06*	09 43·0^{3}	+02 21^{5}	7	869	09 43·6	+02 36	17·4
10—*021*	10 59·8^{2}	—00 52^{5}	23	1148	10 59·8	—00 48	17·6
11+*09*	11 38·4^{4}	+05 43^{8}	8·2:	1346	11 38·5	+05 58	16·8
11—*113*	11 47·1^{3}	—11 47^{6}	17	1391	11 47·3	—12 02	18·0
12—*01*	12 01·8^{3}	—04 36^{6}	12	1453	12 01·0	—04 23	17·8
				1458	12 01·5	—04 48	17·3
12—*08*	12 15·9^{3}	—04 47^{7}	16	1517	12 16·5	—04 45	16·6
12—*111*	12 34·0^{3}	—14 13^{7}	9·6	1572	12 34·1	—14 26	17·3
12—*113*	12 37·3^{5}	—15 38^{6}	14+	1583	12 37·8	—15 42	17·8
12—*019*	12 48·0^{2}	—01 36^{6}	14	1620	12 47·1	—01 20	17·2
13+*09*	13 40·3^{4}	+02 20^{9}	13	1773	13 39·6	+02 29	15·6
13—*117*	13 59·1^{2}	—11 35^{5}	13	1836	13 58·9	—11 24	17·7
14+*01*	14 01·6^{3}	+09 22^{7}	28	1850	14 01·0	+09 22	17·5
14—*018*	14 53·5^{2}	—05 44^{4}	16	1994	14 53·6	—05 39	17·7
15+*03*	15 08·6^{2}	+06 08^{6}	24	2029	15 08·4	+05 57	16·0
15+*06*	15 14·4^{5}	+00 18^{8}	16	2050	15 13·7	+00 17	17·1
15+*05*	15 14·2^{2}	+07 11^{6}	140	2052†	15 14·2	+07 11	15·0

† Coincidences with single or double galaxies in these clusters are noted in Tables 1 and 2.

TABLE 3 (*Continued*)

Radio Source				Cluster			
Ref. No.	Position (1950)		Flux Density (10^{-26} Wm^{-2} $(c/s)^{-1}$)	Ref. No.	Position (1950)		m_p
	R.A. h m	Dec. ° ′			R.A. h m	Dec. ° ′	
15+0*11*	15 37·4^{3}	+06 08^{8}	22	2109	15 38·1	+06 11	17·4
15—0*12*	15 38·1^{5}	—01 54^{6}	37 (21)	2103	17 37·3	—02 01	17·1
20—1*11*	20 45·0^{3}	—18 20^{7}	15	2328	20 45·4	—18 00	16·4
21—1*20*	21 48·7^{3}	—15 54^{7}	8·8	2382	21 49·3	—15 53	16·0
21—1*21*	21 48·9^{3}	—19 53^{7}	18+	2384	21 49·5	—19 47	15·9
22—0*12*	22 29·2^{4}	—08 33^{6}	15	2448	22 29·1	—08 42	16·0
22—1*15*	22 35·8^{2}	—17 36^{6}	17	2462	22 36·4	—17 38	16·2
22—0*14*	22 36·9^{3}	—04 13^{6}	16	2464	22 36·6	—04 14	17·8
22+0*15*	22 57·2^{4}	+09 43^{8}	15	2512	22 57·0	+09 50	17·1
23—1*3*	23 07·7^{3}	—10 45^{7}	7·6	2544	23 07·6	—11 05	17·2
23+0*2*	23 08·2^{3}	+07 28^{6}	22	2551	23 09·0	+07 38	17·5
23—1*4*	23 09·6^{3}	—12 54^{6}	11	2549	23 08·7	—13 05	17·0
23—08	23 15·6^{3}	—02 29^{7}	9·8	2571†	23 16·0	—02 33	17·6
23—1*12*	23 22·6^{2}	—12 29^{5}	30	2597†	23 22·7	—12 24	16·6
23—1*16*	23 27·6^{2}	—18 47^{6}	13	2612	23 28·3	—18 56	17·7
23—0*15*	23 38·0^{3}	—00 08^{6}	11	2644†	23 38·5	—00 12	16·6

coincidences with clusters in Abell's catalogue. Photographic magnitudes given in Tables 1 and 2 have been taken, where possible, from Humason, Mayall, and Sandage (1956), de Vaucouleurs (1957), or Holmberg (1958). Where the galaxy is too faint for inclusion by these authors, estimates have been made using a comparison sequence of images of galaxies calibrated in photo-red magnitudes and kindly made available by Dr. G. O. Abell. The red magnitudes have then been transformed to photographic, using the data of Abell (1958) and Holmberg (1958); it is expected that the accuracy is about 1 magnitude. In several cases photographs with the 200-in. Hale telescope have been referred to; this unpublished material was kindly made available by Dr. R. L. Minkowski. Also, several of the coincidences noted in the tables had been recognized by Dr. Minkowski in an earlier unpublished investigation of a portion of the area examined here, using essentially the same data.

In Table 1 are collected those coincidences for which the available angular size data are consistent with an identification. Criteria for such consistency are by no means well established and, in general, considerable latitude has been allowed. From an examination of known and well-established identifications it has been concluded that, with the present aerial spacings, a radio galaxy of photographic magnitude 19 would have an expected equivalent angular size of $\frac{1}{2}$ min of arc, with an uncertainty of about a factor of 2 or 3. It has also been borne in mind that intrinsically strong radio sources are likely to have a greater extent in space than intrinsically weak sources. A number of coincidences excluded from Table 1 because of inappropriate sizes are given in Table 2, along with those coincidences in which the radio source is too faint for a size measurement. Since all the faint sources and all those with incompatible sizes are included in Table 2, it is possible that not many of the coincidences are significant. In all, there are 30 sources in Table 1 and 16 sources in Table 2. In recording the difference of radio and photographic magnitudes the estimated radio magnitude at $1\cdot9$ m wavelength is quoted, based on the magnitude system of Hanbury Brown and Hazard, together with scale and spectrum adjustments described before (Mills 1959). The relation used is $m_{1\cdot9}=-53\cdot4-2\cdot5\log S_{3\cdot5}+0\cdot8$. In this scale a flux density of 10^{-25} $\mathrm{Wm^{-2}\,(c/s)^{-1}}$ at $3\cdot5$ m wavelength corresponds to a magnitude of $9\cdot9$.

A brief discussion of each coincidence is given in the " notes " column and some of their common features are examined in Section VI. One coincidence, however, that with the source 16+0*10* (Hercules A) needs detailed discussion. This source had earlier been identified by Minkowski (1957) with the highly peculiar double galaxy noted in the table. This identification, together with others, has been used to derive a collimation error for the $3\cdot5$ m Cross; the position of the source given by Mills, Slee, and Hill (1958) includes the derived correction of $+4^s$ Right Ascension and agrees quite well with the galaxy position. However, the more accurate Right Ascension of the 3C position appears incompatible with an identification agreeing precisely with the uncorrected Sydney position. A new determination has been attempted at Sydney, basing the collimation correction on the positions of two well-established identifications, Virgo A and Hydra A, closely straddling the source Hercules A in declination. However, the result was essentially the same, the indicated correction being $+3^s$; this position is quite compatible either with the 3C position or the galaxy position, and doubt concerning the identification arises because of the claimed accuracy of the former. However, inspection of the Sky Survey and 200-in. telescope plates shows that there are no galaxies in the immediate vicinity bright enough to suggest a radio size as great as that measured, except the system noted, and even this is somewhat faint. One possibility is that here we have a close blend of radio sources, the dominant one being associated with the double system, the weaker with one of numerous faint galaxies in a north preceding direction; examination with an instrument of very high resolving power in both coordinates seems necessary to clarify the situation.

Coincidences between radio sources and clusters are listed in Table 3. Of the 55 coincidences noted, it was shown that the chance expectation is 16 so that the probability of a selected coincidence being significant is not so high as in Table 1. In every case the apparent radio emission is considerably more than anticipated from the integrated emission of " normal " galaxies in the cluster. Several of these radio sources have, however, also been listed in Tables 1 and 2, indicating that, in these cases at least, the radiation is more likely to be originating in a single peculiar system within the cluster than in the cluster as a whole; such cases are marked by a dagger in Table 3. It is not possible to decide at present whether the remaining significant coincidences are similar or whether one has examples of "radio clusters" where radiation from the intergalactic material reaches abnormally high values.

V. The Radio Luminosity Function

Interpretation of statistical analyses connected with the distribution of radio sources requires, as a starting point, some knowledge of the radio luminosity function, that is, knowledge of the number of radio sources in a given volume of space as a function of their emission. Since there is, at present, no reliable way of determining directly the distance of a radio source by radio means, one must proceed by identification of the sources and the application of optical criteria of distance. In the following analysis identifications with galaxies only are considered.

There are sufficient possible identifications resulting from the present investigation to take the first step in determining the radio luminosity function. Thus, if it be assumed that this function is constant throughout the volume of space accessible to the present observations, then we determine at the outset the probability of a galaxy, chosen at random, having a specified ratio of radio to optical emission. The result obtained with the present material can only be regarded as provisional, to be improved when better determined positions and angular sizes become available ; in particular, the operation of selection effects, necessarily imposed by the quality of the data, allows the existence of distant unidentified sources of high radio emission.

In the next step, absolute values for radio emission and space density may be obtained from optically derived properties of the galaxies. However, the latter step is not taken explicitly here because the optical data are at present inadequate. Instead, some statistical properties of the radio sources are deduced from the probability function above, and compared directly with observation, making some appropriate simplifying assumptions where necessary.

For simplicity, also, the initial assumption will be made that red-shift effects are negligible over the range in which identifications have been sought. A later analysis in which these are considered indicates that errors will be small compared to those arising from the uncertainties in identification and small-number statistics.

(*a*) *Derivation*

We shall for brevity define the ratio of radio to optical emission of a galaxy by $\underline{m}=m_{1\cdot 9}-m_p$. Then we may write $P_{\underline{m}}\cdot\Delta\underline{m}$ as the probability that a galaxy chosen at random has $\underline{m}$ between $\underline{m}-\frac{1}{2}\Delta\underline{m}$ and $\underline{m}+\frac{1}{2}\Delta\underline{m}$. Now the area searched systematically for identifications is very close to 10^4 square degrees so that the number of galaxies brighter than m_p in the chosen area can be obtained from Hubble's (1936) relation, on ignoring the red-shift correction, as

$$\log N=0\cdot 6m_p-9\cdot 2+4\cdot 0=0\cdot 6m_p-5\cdot 2,$$

whence

$$\log P_{\underline{m}}\cdot\Delta\underline{m}=\log n_{\underline{m}}\cdot\Delta\underline{m}-0\cdot 6m_p+5\cdot 2, \qquad \ldots\ldots\ldots\ (1)$$

where $n_{\underline{m}}\cdot\Delta\underline{m}$ is the number of identifications with galaxies brighter than m_p having $\underline{m}$ lying between $\underline{m}-\frac{1}{2}\Delta\underline{m}$ and $\underline{m}+\frac{1}{2}\Delta\underline{m}$.

Restricting attention to identifications with $m_{1\cdot 9}$ brighter than $9\cdot 2$ ($S_{3\cdot 5}>2\times 10^{-25}$ Wm^{-2} (c/s)$^{-1}$), which have been looked for systematically, it is evident that we can have a complete set of identifications only with galaxies brighter than

$$m_p=9\cdot 2-\underline{m}.$$

Substituting this in (1) we have for this set of identifications

$$\log P_{\underline{m}}\cdot\Delta\underline{m}=\log n_{\underline{m}}\Delta\underline{m}+0\cdot 6\underline{m}-0\cdot 3. \qquad (2)$$

For single galaxies which have been investigated systematically only to magnitude 16 this expression is correct for $\underline{m}$ greater than $-6\cdot 8$. For double galaxies investigated to $m_p=19$ the limiting value of $\underline{m}$ is about $-9\cdot 8$. It is evident that, for single galaxies with $\underline{m}<-6\cdot 8$ and for double galaxies with $\underline{m}<-9\cdot 8$, N is a constant defined by the limiting photographic magnitude. Thus for single galaxies with $\underline{m}<-6\cdot 8$

$$\begin{aligned}\log P_{\underline{m}}\cdot\Delta\underline{m}&=\log n_{\underline{m}}\cdot\Delta\underline{m}+0\cdot 6\times -6\cdot 8-0\cdot 3\\&=\log n_{\underline{m}}\cdot\Delta\underline{m}-4\cdot 4, \qquad (3)\end{aligned}$$

and similarly for double galaxies with $\underline{m}<-9\cdot 8$

$$\log P_{\underline{m}}\cdot\Delta\underline{m}=\log n_{\underline{m}}\cdot\Delta\underline{m}-6\cdot 2. \qquad (4)$$

To construct the probability function the data of Table 1 have been used. It is not suggested that all coincidences listed in this Table are real identifications, or that all identifications in the area are included, but it appears to be an adequate sample for making a preliminary analysis. The photographic magnitudes of two galaxies in heavily obscured regions (coinciding with the sources 17−06 and 17−23) have been corrected by 4 magnitudes and the sources 14−019 and 22−09 have been omitted because they do not fit into the scheme used in deriving equations (2), (3), and (4) ; the former has too low a flux density, the latter an associated galaxy which is too faint. In order to obtain sufficient numbers in each magnitude interval, $\Delta\underline{m}$ has been taken as 2 magnitudes ; because of this large interval the equations are no longer exactly correct, but the uncertainties in the data do not warrant alteration. Likewise, the numbers are too few to differentiate between single and double galaxies, and in Table 4, where the results are tabulated, they are lumped together. When equations (3) and (4) had to be applied the probabilities were computed separately and then added.

The probability function is plotted in Figure 1, where it is evident that, between $\underline{m}=+1$ and $\underline{m}=-13$, the straight line defined by

$$\log P_{\underline{m}}=-1\cdot 0+0\cdot 42\underline{m} \qquad (5)$$

gives a reasonable approximation to the observed points. The point marked by a cross at $\underline{m}=+1$ has been derived from the data on normal galaxies (Mills 1959) ; about 50 per cent. of spirals representing about 25 per cent. of all galaxies had values for $\underline{m}$ between $+0\cdot 5$ and $+1\cdot 5$, leading to $P_{+1}\simeq\frac{1}{4}$.

(b) *Applications of the Luminosity Function*

Let us now consider in a general way the flux densities and numbers of the radio sources predicted by a law of this form and compare them with the actual observations. Initially we will ignore cosmological effects; later they will be taken into account.

TABLE 4

DERIVATION OF THE PROBABILITY FUNCTION FROM THE OBSERVED COINCIDENCES

The interval Δm is taken as 2 magnitudes

$\underline{m}$	$n_{\underline{m}} \cdot \Delta \underline{m}$	$\log P_{\underline{m}}$
+1	—	—
−1	1	−1·2
−3	4	−1·8
−5	3	−3·1
−7	9	−3·8
−9	7	−5·1
−11	3	−6·0
−13	1	−6·5

Substituting equation (5) in equation (1), we find the following relationship between $n_{\underline{m}}$, $\underline{m}$, and m_p

$$\log n_{\underline{m}} = -6\cdot 2 + 0\cdot 42\underline{m} + 0\cdot 6 m_p,$$

or, if we take $\mathscr{N}_{\underline{m}}$ as the total number of sources over the whole sky in an interval $\Delta\underline{m} = 2$, we have

$$\begin{aligned}\log \mathscr{N}_{\underline{m}} &= -5\cdot 3 + 0\cdot 42\underline{m} + 0\cdot 6 m_p \\ &= -5\cdot 3 - 0\cdot 18\underline{m} + 0\cdot 6 m_{1\cdot 9}. \quad \ldots\ldots\ldots\ldots (6)\end{aligned}$$

In defining a family of uniformly distributed radio sources, the most convenient parameter is the flux density of the first " average " source, S_0 (Mills and Slee 1957). This may be derived for each value of $\underline{m}$ by putting $\mathscr{N}_{\underline{m}} = 1$ in equation (6), and converting $m_{1\cdot 9}$ to flux density at $3\cdot 5\ m$ using the formula in the preceding section, thus

$$S_{0,\underline{m}} = \text{antilog}\,(-24\cdot 60 - 0\cdot 12\underline{m}). \quad \ldots\ldots\ldots\ldots (7)$$

Thus we have

$$\begin{aligned}S_{0,-13} &= 9\cdot 0 \times 10^{-24}\ \text{Wm}^{-2}\ (\text{c/s})^{-1} \\ S_{0,-11} &= 5\cdot 3 \times 10^{-24}\ \text{Wm}^{-2}\ (\text{c/s})^{-1}, \\ S_{0,-9} &= 3\cdot 0 \times 10^{-24}\ \text{Wm}^{-2}\ (\text{c/s})^{-1}, \text{ etc.}\end{aligned}$$

To obtain the flux density S_0 of the first " average " source of the whole population, we note that the total number of sources with flux densities greater than S is given by

$$\begin{aligned}\mathscr{N} &= (S_{0,+1}/S)^{3/2} + (S_{0,-1}/S)^{3/2} + (S_{0,-3}/S)^{3/2} + \ldots \\ &= (S_0/S)^{3/2},\end{aligned}$$

whence

$$S_0^{3/2} = S_{0,+1}^{3/2} + S_{0,-1}^{3/2} + S_{0,-3}^{3/2} + \ldots$$

If the population is limited to $\underline{m}=-13$, which represents the greatest radio emission recognized, we may perform the sum and find that

$$S_0=1\cdot 3\times 10^{-23}\ \mathrm{Wm^{-2}\ (c/s)^{-1}}.$$

From the direct counting of observed sources Mills and Slee (1957) concluded that $S_0=2\cdot 1\times 10^{-23}\ \mathrm{Wm^{-2}\ (c/s)^{-1}}$. Since it was also found that a substantial proportion of the sources were of large apparent size and therefore not represented by the present class of identifications, it would appear that, within the uncertainty of the data, the agreement is good. However, cosmological effects have been ignored and before a definite conclusion can be reached it is necessary to examine the results in a more realistic universe.

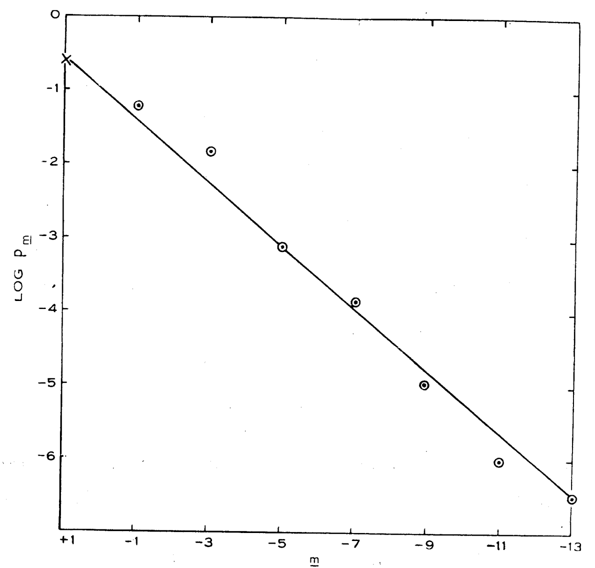

Fig. 1.—The probability that a galaxy chosen at random has radio emission defined by $\underline{m}$, where $\underline{m}$ is the difference between the radio and photographic magnitudes of the galaxy ($m_{1\cdot 9}$—m_p).

No attempt will be made to decide between different cosmologies, but one particular type will be worked out in detail to illustrate the kind of effects expected. The Einstein-de Sitter universe is chosen as a model; it is the simplest of the "exploding" models and is characterized by the absence of curvature and cosmological constant. If the assumption is made that the total number of radio sources of any given emission has remained unaltered during the evolution of the universe it turns out that the number counts may be expressed by a very simple relation, which is derived in Appendix I. Thus, for a class of source of fixed emission we have the relation

$$S=\frac{S_0}{\mathcal{N}^{\frac{2}{3}}}\left[1-\left(\frac{\mathcal{N}}{\mathcal{N}_0}\right)^{\frac{1}{3}}\right]^{4+2\gamma}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where $\mathcal{N}$ is the number of sources with flux density greater than S, $\mathcal{N}_0$ is the total number of such sources in the observable universe, and the spectrum of the sources is of the form

$$S \propto \lambda^{\gamma}.$$

The correction to the normal source count relation is given by the bracketed term. $\mathcal{N}_0$ is derived fundamentally from the measured red-shifts of identified galaxies, but for clarity we will assume a particular value of Hubble's constant, namely, $H=100$ km/s/megaparsec, and calculate the space density of the various source classes and their absolute luminosities. The final source counts, however, are independent of the value chosen for H.

It is first assumed that all identified galaxies have the same absolute photographic magnitude. Some such assumption is necessary to proceed because of the present inadequate data; it is not unreasonable as shown by Dewhirst (1959), at least for those galaxies of the highest radio emission which dominate the source counts and for which cosmological corrections are required. The mean, absolute photographic magnitude of six identified galaxies listed by Dewhirst is $M_p=-20\cdot 5$, also using $H=100$ km/s/megaparsec. This value will be adopted in the present calculations although it may eventually prove to be too luminous, because of selection effects. Thus the absolute radio luminosity of a source is given by

$$\begin{aligned} L_{\underline{m}} &= 4\pi(3\cdot 09\times 10^{17})^2 \text{ antilog } -0\cdot 4(52\cdot 6+M_p+\underline{m}) \text{ W (c/s)}^{-1} \\ &= 1\cdot 7\times 10^{23} \text{ antilog } -0\cdot 4\underline{m} \text{ W (c/s)}^{-1} \text{ at } 3\cdot 5 \text{ m wavelength,} \end{aligned}$$

for example,

$$L_{13}=2\cdot 7\times 10^{28} \text{ W (c/s)}^{-1}.$$

It is readily shown, by consideration of the number of sources in a given spherical volume, that the space density, $\rho_{\underline{m}}$, is given by the relation

$$\rho_{\underline{m}}=6\sqrt{\pi}\cdot(S_{0,\underline{m}}/L_{\underline{m}})^{3/2}, \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

where $S_{0,\underline{m}}$ is obtained as in (**7**). It is also shown in Appendix I that

$$\mathcal{N}_0=36\pi\rho_2(cT)^3,^*$$

where T is the reciprocal of Hubble's constant, whence

$$\begin{aligned} \mathcal{N}_{0,\underline{m}} &= 216\pi^{3/2}(cT)^3(S_{0,\underline{m}}/L_{\underline{m}})^{3/2} \\ &= 1\cdot 8\times 10^9 \text{ antilog } 0\cdot 42m, \quad \ldots\ldots\ldots\ldots \quad (10) \end{aligned}$$

for example,

$$\mathcal{N}_{0,-13}=6\cdot 4\times 10^3.$$

In Figure 2 the source counts expected from equations (**8**) and (**10**) have been plotted for values of $\underline{m}$ between $+1$ and -13. The assumption is made that $\gamma=+1\cdot 0$ for all sources. Also shown are the combined counts and those obtained

* The symbol ρ_2 is used in Appendix I to denote the space density of objects at the present time, i.e. it is equivalent to $\rho_{\underline{m}}$ above.

from direct observation. The latter have been obtained from the known strong sources in the whole sky (open circles) and the catalogue of Mills, Slee, and Hill (1958) covering about 3 steradians (solid circles). The standard errors in the numbers due to statistical fluctuations are indicated by vertical wings. To obtain the best estimate of the true source count, corrections are necessary at low flux densities; these have been calculated at 10^{-25} Wm^{-2} (c/s)$^{-1}$ and 2×10^{-25} Wm^{-2} (c/s)$^{-1}$ using the data of Mills and Slee (1957), plus an additional small correction for a type of error discovered subsequently. This error arises

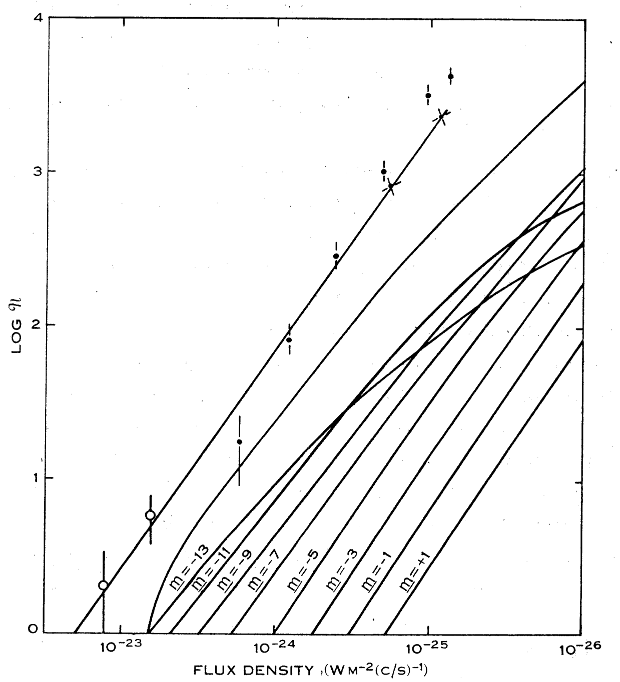

Fig. 2.—Comparison of the observed source counts with those predicted by the derived radio luminosity function. The observational points are shown as dots or crosses, depending on their origin, having vertical wings indicating the standard error due to statistical fluctuation. Two points corrected for the instrumental effects which occur at low flux densities are indicated by crosses. Expected counts for each class of source are labelled with the corresponding value of $\underline{m}$; the total expected count which is the sum of these is also shown.

from the systematic over-estimation of flux densities not very much above the sensitivity limit; it is a partially subjective effect, but very similar between different observers. It will be discussed in a later publication. The corrected points are indicated by crosses, and a straight line drawn through these represents the true source counts as closely as possible with the present data.

It appears that the numbers derived from Table 1 are too low by a factor of about 3 to account for all the observed sources. However, substantial numbers of the sources appear to be of large size, possibly irregularities in the galactic corona or relatively close blends (e.g. two or more radio galaxies in a cluster); these would not appear in Table 1 and would not contribute to the radio luminosity function. They comprise about 30 per cent. of listed sources having flux density near 5×10^{-25} Wm^{-2} (c/s)$^{-1}$ and, perhaps, as indicated by preliminary results with the Sydney angular size interferometer, an even greater proportion of fainter sources. One is therefore left with a discrepancy of a factor of 2 which, in view of the uncertainty in the data, is barely significant. However, there are several possible additional identifications between strong sources and galaxies of apparently normal appearance which are too faint for inclusion in Table 1 although the radio sizes are admissible. These could quite well raise the probability function at high emissivities sufficiently to counteract any deficiency. They are clearly a subject for future investigation both at radio and optical wavelengths. A further possibility, that there is a *significant* number of sources having $\underline{m} < -13$, does not, at present, appear very likely, since these would drastically alter the form of the source counts.

One of the most striking features of the computed curve is the small influence of cosmological effects. There is no appreciable curvature above about 10^{-25} Wm^{-2} (c/s)$^{-1}$ where the mean slope is about $-1 \cdot 3$, and between 10^{-25} and 10^{-26} Wm^{-2} (c/s)$^{-1}$ the slope decreases to only about $-1 \cdot 0$, although the sources of highest emission show very marked effects in this region. The reason, of course, is the dilution by the intrinsically weaker sources, which being closer, show little effects and indeed initially tend to increase the numerical value of the slope. The difference between various cosmologies would also be masked in this way and, since this difference is unlikely to be large in the first place (e.g. Hoyle 1959), the simple counting of observed sources is unlikely to be a very sensitive test.. However, suitable angular size data could prove very valuable by allowing the separation of the various classes of source.

Finally, one may compute the integrated extragalactic emission from the class of radio sources defined by Figure 1. It is shown in Appendix I that the equivalent brightness temperature of the integrated background in an Einstein-de Sitter universe is given by

$$T_{\underline{m}} = \frac{L_{\underline{m}} \rho_{\underline{m}} \lambda^2 c T}{4\pi k(5+2\gamma)}. \qquad \qquad (11)$$

Making the assumptions as before we find

$$T_{\underline{m}} = 3 \cdot 1 \text{ antilog } 0 \cdot 02\underline{m} \text{ degK}$$

whence

$$T = \sum_{\underline{m}=+1}^{\underline{m}=-13} T_{\underline{m}} = 20\ ^{\circ}\text{K}.$$

This is a lower limit for two reasons : (*a*) it is probable that the derived radio luminosity function does not include all extragalactic sources, as shown above, and (*b*) in deriving the luminosity function it was assumed that all galaxies identifiable as radio emitters had an absolute magnitude of $-20 \cdot 5$. While this value is probably appropriate for deriving the cosmological correction to the counts of sources of high emission, for which it was used originally, it is inappropriate for calculating the integrated emission of the " normal " spiral galaxies which have the greatest weight in determining T ; these would have a smaller emission, a higher space density, and a greater integrated temperature. As an example, if we put $M_p = -16 \cdot 5$ (Hubble's mean value corrected for the new value of H) instead of $-20 \cdot 5$, the integrated emission is increased by 2 magnitudes (equations (**9**) and (**11**)) to 125 °K. Shain (1959) has concluded that the most probable value of the extragalactic contribution to the observed temperatures near the Galactic poles is about one-third of the total, or about 250 °K, but he stated that it could be very much less.

VI. Discussion

It follows from the results presented in the last section that the Class II sources of small angular size are likely to be extragalactic. Analysis suggests that these sources can be substantially represented by a class defined by the possible identifications in Table 1, possibly with the addition of a class of apparently normal galaxies of relatively high radio emission.

There is less information about the sources of large size. In a few cases these may be identified with clusters of galaxies, either representing radiation from the intergalactic material in the cluster or from two or more strongly emitting galaxies. However, few of the sources coinciding with clusters in Table 3 are listed as " extended " or " perhaps extended " in the Sydney catalogue and, conversely, extended Class II sources do not show a significantly higher correlation with clusters. It is therefore concluded that rich clusters of the type listed by Abell are not associated with the majority of the extended radio sources. The most likely explanation appears to be that these sources are mainly galactic irregularities and/or blends of closely spaced " radio galaxies ". Angular size data which are being collected at present should throw more light on this problem and it will not be discussed here any further.

It is perhaps appropriate to consider a possibility which arises because of the apparently continuous nature of the radio luminosity function. If radio galaxies are formed only with the highest emission by a rare cataclysmic process and thereafter the emission slowly decays to a normal value, the number of galaxies having a luminosity between L and $L+\mathrm{d}L$ will be inversely proportional to $\mathrm{d}L/\mathrm{d}t$. Assuming a luminosity function of the form derived in the preceding section, it is easily shown that this would require a decay law approximately of the form

$$L \simeq L_0/(1+At),$$

where A is a constant and t the time after the outburst. However, the synchrotron mechanism does not easily lend itself to a decay law of this kind. For example, if the outburst produces a spectrum of relativistic electrons defined by the power law, $n\mathrm{d}E \propto (1/E^{\beta})\mathrm{d}E$ (where $\beta \approx 3$), the subsequent decay of the luminosity due to radiation losses at a fixed frequency and in a constant magnetic field is readily shown to be

$$L = L_0(1-Bt)^{\beta-2},$$

where B is a constant related to the frequency chosen and the magnetic field. While it appears that a suitably varying magnetic field could produce the decay law suggested by observation, in fact no physically plausible variation has been found which will do so. Also, other features are expected in a decaying source, namely, a change in the radio spectrum with age (i.e. with absolute radio luminosity) and a high frequency cut-off in the radiation which is also a function of age. Present observational evidence does not appear to support the existence of these features and it seems that the luminosity function is probably not formed as the result of such a process. If a radio galaxy is a transient phenomenon, the luminosity function would appear to be determined primarily by the peak value of the emission rather than the decay law.

Let us now consider the galaxies listed in Table 1, which are the most likely to be real identifications. These galaxies have no obvious common feature, as all types of system are represented ; they do, however, separate into two distinct classes, single galaxies and double galaxies. Members of these same classes have already been recognized in identifying the strongest radio sources ; e.g. the radio sources Virgo A and Fornax A are identified with single galaxies and Cygnus A, Hydra A, Hercules A, and Perseus A with doubles ; the source Centaurus A is a possible member of the latter class also.

Identifications with single galaxies are in general uncertain, for there appears to be no reliable optical clue which indicates excess radio emission. The galaxy NGC4486, identified with Virgo A, has, it is true, a very blue " jet " extending from the nucleus. However, this is recognizable only because the galaxy is so close ; similar features would not be visible usually in the single galaxies of Table 1 and, in fact, no abnormal features were noted. In Table 2 one galaxy, associated with the source 04+0*14*, displays heavy absorption in the spiral arms, but it is not known if this is a significant form of abnormality. One cannot hope to derive much useful information from optical studies of the single galaxies listed.

The double galaxies are rather more interesting. If these are real identifications, as appears likely in the majority of cases, they must be physical rather than optical doubles. The question arises whether they are colliding (Baade and Minkowski), separating (Ambartsumian), or orbiting. The first two possibilities can be separated from the third on a statistical basis by measurement of the radial velocities of the two components, and it is hoped that this information will be available before long.

The collision hypothesis does not appear to stand up to a close examination ; the numbers of colliding galaxies in the Universe are expected to be quite small, in fact quite negligible outside the centres of dense clusters, as shown by Spitzer and Baade (1951), and, if the further limitation is imposed that only giant colliding galaxies produce markedly excess radio emission (to agree with the absolute luminosities of identified radio galaxies), the interpretation is completely inadequate. The ideas of Ambartsumian (1956) are hard to understand, since he suggests that some of the double galaxies may be recently formed systems, separating and forming two nuclei ; the application of these ideas to very old galaxies containing a high proportion of Population II stars, as some of the identified galaxies appear to be, does not appear legitimate. However, there is some observational support for the suggestion in an earlier identification made with the system associated with NGC6166. Dewhirst (1959) describes this as containing within a common envelope two or possibly three nuclei in addition to the main system with a velocity difference between the brightest components of about 1500 km/s.

In contrast to the general implausibility of these suggestions it appears that two closely orbiting galaxies are quite likely to build up strong magnetic fields as a result of interaction of the surrounding very tenuous gas The presence of a normal concentration of relativistic electrons could then lead to an abnormally high radio emission. There is no real evidence that this sort of process occurs, however, and NGC6166 could certainly not be explained in this way. Since none of these possibilities appears plausible in all cases, perhaps a radio source can be associated with any of the three.

Of particular interest to the double galaxy situation are the results on the distribution of radio emission across a galaxy. Here again we appear to have evidence of duplicity. The Cygnus A source, with its two concentrations on either side of a double galaxy, is now well established, and recently Wade (1959) has shown that the extended corona of the Centaurus A source also appears to consist of two symmetrically situated concentrations with about the same apparent spatial separation as Cygnus A. The situation in Centaurus A is complicated by the existence of a small central source responsible for about 25 per cent. of the total emission and apparently coinciding with the band of dust crossing NGC5128 (Mills 1953). A more detailed study of this small source by Twiss, Carter, and Little (in press) shows that it, too, is a double system. The possibility that these are all toroidal sources is not supported by the detailed distributions given, and the present evidence does appear to suggest that they are real doubles.

In view of the scanty data it is rather profitless to speculate about the processes by which optical and radio double galaxies are formed. Rather, it is necessary to collect a great deal more information both at optical and radio wavelengths, particularly about the coincidences listed in Table 1. In this way it may be possible to separate the basic factors from a mass of probably irrelevant detail.

VII. Acknowledgments

Examination of the original plates of the National Geographic Society–Palomar Observatory Sky Atlas was carried out during a two-month period at the California Institute of Technology, supported financially by a grant from the National Science Foundation.

The author is indebted to Dr. D. W. Dewhirst and Professor M. Ryle for making available material prior to publication, and, in particular, to Dr. R. L. Minkowski whose advice and freely given unpublished data helped very materially.

VIII. References

Abell, G. O. (1958).—*Astrophys. J. Suppl. Ser.* **3**: 211.

Ambartsumian, V. A. (1956).—Proceedings of the 5th Conference on questions of cosmogony (Radioastronomy), Moscow, p. 413.

Bondi, H. (1952).—" Cosmology." (Cambridge Univ. Press.)

Dewhirst, D. (1959).—" Paris Symposium on Radio Astronomy." (Ed. R. N. Bracewell.) p. 507. (Stanford Univ. Press.)

EDGE, D. O., SHAKESHAFT, J. R., MCADAM, W. B., BALDWIN, J. E., and ARCHER, S. (1959).—*Mem. R. Astr. Soc.* **68** : 37.

GODDARD, B. R., WATKINSON, A., and MILLS, B. Y. (1960).—An interferometer for the measurement of radio source sizes. *Aust. J. Phys.* **13** (4). (In press.)

HOLMBERG, E. (1958).—*Medd. Lunds. Astr. Obs.* Ser. II, No. 136.

HOYLE, F. (1959).—" Paris Symposium on Radio Astronomy." (Ed. R. N. Bracewell.) p. 529. (Stanford Univ. Press.)

HUBBLE, E. (1936).—*Astrophys. J.* **84** : 517.

HUMASON, M. L., MAYALL, N. V., and SANDAGE, A. R. (1956).—*Astr. J.* **61** : 97.

MILLS, B. Y. (1953).—*Aust. J. Phys.* **6** : 452.

MILLS, B. Y. (1959).—" Handbuch der Physik." Vol. 53, p. 239. (Springer-Verlag : Berlin.)

MILLS, B. Y., and SLEE, O. B. (1957).—*Aust. J. Phys.* **10** : 162.

MILLS, B. Y., SLEE, O. B., and HILL, E. R. (1958).—*Aust. J. Phys.* **11** : 360.

MINKOWSKI, R. L. (1957).—" Radio Astronomy, Symposium No. IV of the International Astronomical Union." p. 107. (Cambridge Univ. Press.)

SHAIN, C. A. (1959).—" Paris Symposium on Radio Astronomy." (Ed. R. N. Bracewell.) p. 328. (Stanford Univ. Press.)

SPITZER, L., and BAADE, W. (1951).—*Astrophys. J.* **113** : 413.

TWISS, R. Q., CARTER, A. W. L., and LITTLE, A. G. (1960).—Brightness distribution over some strong sources at 1427 Mc/s. *Observatory.* (In press.)

DE VAUCOULEURS, G. (1957).—*Ann. Obs. Houga* II, No. 1.

WADE, C. M. (1959).—*Aust. J. Phys.* **12** : 471.

APPENDIX I

Relations in an Einstein-de Sitter Universe

This relativistic model universe is characterized by absence of curvature and cosmological constant. It is well known (e.g. Bondi 1952) that the appropriate metric is given by

$$ds^2 = dt^2 - R^2(dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\theta^2),$$

where

$$R = ct^{\frac{2}{3}}.$$

Denoting properties at the time of emission of the radiation by subscript 1, and at the time of reception by subscript 2, we may write down the following relations, using conventional notation.

The present time $t_2 = T^{\frac{2}{3}}$, where $T = 1/H$.

If $z = \Delta\lambda/\lambda_0$,

$$1 + z = R_2/R_1 = (t_1/t_2)^{-\frac{2}{3}}.$$

The luminosity distance

$$q_1 = cr_1 R_2 = cR_2 \int_{t_1}^{t_2} dr/R = 3ct_2[1 - (t_1/t_2)^{\frac{1}{3}}].$$

The number of sources of space density ρ_2 within q_1 is then given by

$$\mathcal{N} = \frac{4}{3}\pi\rho_2 q_1^3 = 36\pi\rho_2 c^3 t_2^3 [1 - (t_1/t_2)^{\frac{1}{3}}]^3. \quad \ldots\ldots\ldots\ldots \quad \textbf{(A1)}$$

Whence the total number of sources in the observable universe is obtained by putting $t_1=0$, thus

$$\mathcal{N}_0=36\pi\rho_2 c^3 t_2^3=36\pi\rho_2 c^3 T^3. \quad \ldots\ldots\ldots\ldots\ldots \quad \textbf{(A2)}$$

The flux density of a source of luminosity L_1, at a distance q_1, is given by

$$S=L_1/4\pi q_1^2(1+z)^2.$$

With a spectrum of the form $L\propto\lambda^\gamma$, and in the absence of evolutionary changes in L we may write

$$L_2=L_1(\upsilon_2/\upsilon_1)$$

or

$$S=L_2/4\pi q_1^2(1+z)^{2+\gamma}. \quad \ldots\ldots\ldots\ldots\ldots \quad \textbf{(A3)}$$

From (**A1**), (**A2**), and (**A3**), we have

$$S=\frac{L_2\rho^{\frac{2}{3}}}{6^{\frac{2}{3}}\pi^{\frac{1}{3}}}\,\frac{[1-(\mathcal{N}/\mathcal{N}_0)^{\frac{1}{3}}]^{4+2\gamma}}{\mathcal{N}^{\frac{2}{3}}},$$

which, on using the relation $\rho=6\sqrt{\pi}.(S_0/L)^{3/2}$ (equation (**9**)), becomes

$$S=(S_0/\mathcal{N}^{\frac{2}{3}})[1-(\mathcal{N}/\mathcal{N}_0)^{\frac{1}{3}}]^{4+2\gamma}. \quad \ldots\ldots\ldots\ldots \quad \textbf{(A4)}$$

Consider now the sources in unit solid angle at distance q_1. These contribute a flux $\mathrm{d}B$, given by

$$\mathrm{d}B=S\mathrm{d}n=\frac{\rho_2 L_2}{4\pi(1+z)^{2+\gamma}}\mathrm{d}q_1$$

and the brightness temperature

$$T=\frac{\lambda^2}{2k}\int\mathrm{d}B=\frac{L_2\rho_2\lambda^2}{8\pi k}\int_{z=0}^{z=\infty}\frac{\mathrm{d}q}{(1+z)^{2+\gamma}}$$

$$=\frac{L_2\rho_2\lambda^2}{4\pi k(5+2\gamma)}\cdot cT. \quad \ldots\ldots\ldots\ldots \quad \textbf{(A5)}$$