LIFETIMES OF EXTRAGALACTIC RADIO SOURCES

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ABSTRACT

Statistical data on the space density of bright elliptical galaxies, radio galaxies, clusters of galaxies, and quasi-stellar radio sources are assembled and discussed. Since all galaxies identified with strong radio sources are intrinsically bright elliptical galaxies, there will exist a relation between their space densities and their ages. If the ellipticals are 10^{10} years old, then the data suggest a total harmonic-mean lifetime for the radio-galaxy stage of about 10^9 years A distribution of lifetimes such that the strongest sources live for around 10^6 years and the weaker ones for several billion years would be possible (see Table 2). Rather more speculative considerations about the relation between quasi-stellar radio sources and radio galaxies suggest that the quasi-stellar sources may have a harmonic-mean lifetime of around 10^6 or 10^7 years.

I. INTRODUCTION

Little is known about the lifetimes of extragalactic radio sources. Minimum estimates can be made from the sizes of the sources. These range from about 10 kpc to at least 300 kpc for sources identified with galaxies. If it is assumed that the sources expanded from the galaxy, the corresponding minimum lifetimes are around 10^4 to 10^6 years. Age estimates may also be based on synchrotron models of magnetic fields and high-energy particles, but these would be quite uncertain because the magnetic field strength and the time dependence of the particle injection are poorly or not known. Also there is the possibility that a radiation mechanism other than the synchrotron mechanism is operating in these sources.

It is obviously of interest to get independent information on the lifetimes of radio sources. We shall base this determination on the finding by Matthews, Morgan, and Schmidt (1964; to be referred to as "MMS") that those galaxies that emit strong radio radiation are always elliptical galaxies (including D, N, and db galaxies). Sandage (1964, 1965) has found from the redshift-magnitude relation of these radio galaxies that they belong to the intrinsically brightest galaxies. The ratio of the lifetimes of the radio sources and the brighter ellipticals is reflected in their relative frequency in space under assumptions discussed in § III. Similar arguments relating radio sources and galaxies in general have been used previously by Burbidge (1962). Supporting evidence is obtained from the statistical relation between radio galaxies and clusters of galaxies. The lifetimes of quasi-stellar radio sources may be estimated in similar fashion if the assumption of a relationship with the radio galaxies is valid.

In the next section we assemble the necessary data on the space density of bright elliptical galaxies, radio galaxies, clusters of galaxies, and quasi-stellar radio sources. Lifetimes of radio galaxies are discussed in § III and those of quasi-stellar sources in § IV.

II. SPACE DENSITIES

Bright elliptical galaxies.—We use the redshift-magnitude diagram for elliptical galaxies in Figure 3 of Humason, Mayall, and Sandage (1956; to be referred to as "HMS"). The redshift-magnitude diagram for radio galaxies (Sandage 1965) suggests that essentially all these galaxies are at least 0.6 mag. brighter than the mean line drawn in Figure 3 of HMS. Of the intrinsically *bright* elliptical galaxies so *defined* we count in this figure seventeen galaxies with a radial velocity less than 4000 km/sec. For larger velocities serious incompleteness of the data sets in. Although Figure 3 of HMS contains data for ellipticals with declination above $-30°$, we will assume that it effectively represents 60 per cent of the sky so as to take roughly into account a mild incompleteness of redshift data and the effect of the zone of avoidance. We include the six brightest ellipticals in the Virgo Cluster to get a total-sky estimate of thirty-four ellipticals up to 4000 km/sec. With a Hubble constant of 100 km/sec per Mpc, this corresponds to a space density of 1.3×10^{-4} Mpc^{-3} (Table 1).

The space density of all ellipticals, regardless of absolute magnitude, may be similarly derived from HMS and from the *Reference Catalogue of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964) at a value of around 1×10^{-3} Mpc^{-3}. Hence the bright ellipticals of interest to us constitute about 13 per cent of all catalogued ellipticals.

Radio galaxies.—The space density of radio galaxies can be derived from data given by MMS and by Wyndham (1966). We consider only sources from the 3C revised catalogue (Bennett 1962) which is essentially complete for sources brighter than 9 flux units (10^{-26} W m^{-2}(c/s)$^{-1}$) at 178 Mc/s above declination $-5°$. MMS found that the distribution of radio luminosities L_R showed a deficiency of sources with L_R less than 3×10^{41} erg/sec. Since this may be an effect of selection (see MMS for discussion), we

TABLE 1

SPACE DENSITIES

Object	Density (Mpc^{-3})
Bright elliptical galaxies	$1\ 3\times10^{-4}$
Radio galaxies ($L_R \geqq 3 \times 10^{41}$ ergs/sec) . . .	$0\ 7\times10^{-5}$
Clusters of galaxies (richness class $\geqq 1$)	$0\ 7\times10^{-5}$
Quasi-stellar radio sources	$2\ \ \times10^{-9}$

limit our census of radio galaxies to those with $L_R \geqq 3 \times 10^{41}$ ergs/sec, or more precisely to those with $z^2 S_{178} \geqq 0.008$, where S_{178} is the flux density in flux units and $z = (\lambda - \lambda_0)/\lambda_0$ is the redshift. (For a straight spectrum with spectral index $n = -0.75$, and a range of integration from 10^7 to 10^{11} c/s, we have the relation $L_R = 3.4 \times 10^{43} z^2 S_{178}$ in ergs per second if S is in flux units.) Since for the 3C revised catalogue, $S_{178} \geqq 9$, we must limit the census to redshifts $z \leqq 0.029$. This includes the sources 3C 40, 66, 75, 78, 83.1, 84, 264, 274, 430, and 442 from the MMS list. Data on identifications given by Wyndham (1966) and new redshifts determined by Sandage (1966) suggest that the above list is probably complete. Hence we have ten strong sources with $r \leqq 87$ Mpc above declination $-5°$, corresponding to a space density of 0.7×10^{-5} Mpc^{-3}.

Clusters of galaxies.—Abell (1958) has collected a statistically complete sample of clusters of galaxies in a region covering 37.1 per cent of the sky. All these clusters are of richness class 1 or higher (those with at least fifty members that are not more than 2 mag. fainter than the third brightest cluster member). The complete sample contains ten clusters (Nos. 400, 1228, 1367, 1656, 2147, 2151, 2152, 2197, 2199, and the Virgo Cluster) with distance class 1 or less, for which the redshift is expected to be less than 0.032. The corresponding density of clusters of richness class $\geqq 1$ is 0.7×10^{-5} Mpc^{-3}.

Radio galaxies in clusters of galaxies.—Of the ten strong radio sources mentioned above, only five are in the region of the sky covered by Abell's complete cluster sample. Of these, two (3C 75 and 3C 264) are in clusters of richness $\geqq 1$, or 40 per cent. A statistically more meaningful percentage can be found from the thirty-seven radio galaxies with $L_R \geqq 3 \times 10^{41}$ ergs/sec investigated by MMS for cluster membership; they find that thirteen of these are in clusters of richness $\geqq 1$, or 35 per cent.

Of the ten clusters mentioned above, four (Nos. 400, 1367, 2199, and the Virgo Cluster) contain a strong radio source, or 40 per cent. Analysis of observations of radio emission from clusters of galaxies by Fomalont and Rogstad (1966) shows that out of fifty-four clusters with richness $\geqq 1$, sixteen have a radio source with $L_R \geqq 3 \times 10^{41}$ ergs/sec, or 30 per cent.

We conclude that the radio galaxies with $L_R \geqq 3 \times 10^{41}$ ergs/sec and the clusters of galaxies of richness $\geqq 1$, which appear to be just about equally frequent in space, have 35 per cent of their objects in common.

Quasi-stellar radio sources.—These are the radio sources identified with starlike objects. We assume that their redshifts are of cosmological origin. We attempt to estimate the total number of quasi-stellar sources in the 3C revised catalogue with redshift less than 0.4. For larger redshifts the intrinsically fainter quasi-stellar sources would be too faint for complete identification. Of thirty-three quasi-stellar radio sources in the 3C revised catalogue investigated spectroscopically so far, five (3C 273, 249.1, 48, 351, and 277.1) have redshifts less than 0.4. Since some 30 per cent of the sources in the catalogue are of this kind (Wyndham 1966), it probably contains some eighty to ninety quasi-stellar sources. Since the sources yet to be investigated are relatively faint, one may expect only a few more low redshifts. We estimate the total number with redshift less than 0.4 in the 3C revised catalogue to be between 7 and 10, corresponding to a density of 2×10^{-9} Mpc^{-3}.

This density refers only to quasi-stellar sources with a radio flux density larger than 9 flux units at 178 Mc/s. Hence we have included preferentially quasi-stellar sources with strong radio radiation. A density value referring to sources with a well-defined lower limit of radio luminosity cannot easily be given at present due to the complexity of the radio and optical selection effects and the scarcity of available data for the quasi-stellar sources.

III. LIFETIMES OF RADIO GALAXIES

Let N_E be the number of elliptical galaxies per Mpc^3 that in the past has been a strong radio source ($L_R \geqq 3 \times 10^{41}$ ergs/sec). We assume that all ellipticals were formed a time T_E ago. The number of (elliptical) galaxies per Mpc^3 emitting strong radio radiation is N_R. If all elliptical galaxies under consideration have been a strong radio source for the same total length of time T_R (no distinction is made whether the radio emission is intermittent or not) and if the probability of radio emission is independent of time, then

$$T_R = (N_R/N_E)T_E \, . \tag{1}$$

Next consider the case that the total radio lifetime is different for different radio galaxies. Consider the fraction x_n of the radio galaxies which has a total radio lifetime T_n. If the probability of radio emission is time-independent, then there have been T_E/T_n generations of these sources so the number of elliptical galaxies with radio lifetime T_n is $x_n N_R (T_E/T_n)$. Summation over all lifetimes yields the total number of elliptical galaxies, N_E, so

$$\sum_n \frac{x_n}{T_n} = \frac{N_E}{N_R T_E} \, . \tag{2}$$

Since the right-hand member of equation (2) equals T_R^{-1} according to equation (1), we see that T_R is the *harmonic-mean* lifetime.

Ideally, the value of N_R/N_E in equations (1) and (2) is determined by finding the fraction of bright ellipticals that has strong radio emission. Since no systematic study of the radio emission from intrinsically bright ellipticals is available yet, we use the values of N_E and N_R from Table 1 which had to be derived from different volumes of space and hence are affected by density fluctuations in space. If we take for T_E a value of 10^{10} years, then equation (1) yields for the radio galaxies $T_R = 0.5 \times 10^9$ years. It may be argued that this lifetime is probably an underestimate. First, our adopted value of N_E is likely to be too large because in its determination we used *all* intrinsically bright elliptical galaxies. It may well be that a galaxy that can become a strong radio source should have further, as yet unknown, properties, thus making our present estimate of N_E too large. Second, some galaxies that can become strong radio sources may not have done so yet; these should not have been included in the derivation of N_E. Third, the probability for an elliptical to become a radio source may not be independent of time but rather perhaps a decreasing function of time.

Further information about the value of T_R may be obtained by considering clusters of galaxies. We have seen that 35 per cent of the rich clusters contain a strong radio source. It might be argued that the reason for this high percentage is that each cluster contains a large number of ellipticals. Since the statistics of field galaxies just discussed suggest that for the brighter ellipticals the probability of strong radio radiation is about 5 per cent, the presence of some eight or nine bright ellipticals in the average cluster would be sufficient to explain the high percentage of clusters having a strong radio source. However, of the thirteen radio sources in clusters discussed by MMS (see preceding section) as many as eight are identified with the brightest cluster member, whereas on the above argument we would expect only one or two. This suggests that the brightest cluster galaxy is much more likely to be a strong radio source than the bright ellipticals we have been considering until now. Apparently, then, about one-half of the strong radio sources in clusters of galaxies belong to the brightest cluster member. Since 35 per cent of the clusters were found to contain a strong radio source, we conclude that some 15–20 per cent of the clusters of galaxies contains a radio source belonging to its brightest member. If we now identify N_E in equation (1) with the brightest cluster members and N_R with the radio galaxies in clusters, then we derive a radio galaxy lifetime of 1.5 to 2×10^9 years.

This determination strictly applies to radio galaxies in clusters. It is in reasonable agreement with the value of 0.5×10^9 years derived for radio galaxies in general, of which we argued that it probably was an underestimate. We shall adopt for T_R a value of 1×10^9 years, realizing that a larger value is by no means excluded.

If a radio lifetime of as long as 10^9 years were valid for the strongest sources such as 3C 295 that radiate about 10^{45} ergs/sec, then the total radiated energy of 3×10^{61} ergs would require the nuclear burning of $2 \times 10^9 f^{-1}$ solar masses of hydrogen into helium, where f is the fraction of the nuclear energy that is eventually radiated at radio wavelengths. If this efficiency were as high as 1 per cent, then a whole galactic mass would have to be burned. It is probably more reasonable to assume that the lifetime is shorter for sources with larger radio luminosity. We consider two cases: (*a*) the lifetime is proportional to the inverse of the luminosity; and (*b*) the lifetime goes inversely as the number of sources with different luminosities. Case (*b*) would apply if every source went through the whole luminosity range such that the luminosity function reflects the rate of evolution. The lifetime for different luminosities in each case is computed from equation (2) where we have now adopted the right-hand member as 10^{-9} yr^{-1}. The luminosity function used for case (*b*) is given in Table 2. The total density is adjusted to that of Table 1, while the general gradient which was derived from data in MMS and Wyndham (1966) agrees well with that determined by Roeder and McVittie (1963) and earlier derivations referred to in that paper. The lifetimes found for cases (*a*) and (*b*) are given in Table 2. In case (*a*) the total energy radiated is 6×10^{58} ergs independent of luminosity, in case (*b*) it ranges from about 10^{58} to 10^{59} ergs.

IV. LIFETIMES OF QUASI-STELLAR RADIO SOURCES

No identification of a quasi-stellar radio source with a kind of object of which we can reasonably estimate the lifetime has been made yet. We make the speculative assumption that the similarity in radio properties of the quasi-stellar sources and the radio galaxies (except for the radio sizes) may indicate a relation. If we assume that each radio galaxy of radio luminosity 10^{45} ergs/sec goes through the quasi-stellar stage, then we find from

Table 2 a lifetime of 1 to 5 × 10^6 years. Essentially the same lifetimes are found if radio galaxies of 10^{44} or 10^{43} ergs/sec are involved.

Since the radio sizes of quasi-stellar sources range from less than 0″1 to larger than 10″ (Adgie, Gent, Slee, Frost, Palmer, and Rowson 1965), we consider the possibility that the lifetimes are, say, proportional to the size. If one-half of the sources is taken to have a size 100 times that of the other half (this simple but rather extreme example reflects the apparent dichotomy in the sizes found by Adgie *et al.*), then the shorter life time is 10^6 years and the longer one 10^8 years, if the harmonic-mean lifetime is 2 × 10^6 years.

TABLE 2

LUMINOSITY FUNCTION AND LIFETIMES OF RADIO GALAXIES

L_R (ergs/sec)	DENSITY (Mpc^{-3})	LIFETIMES (yr)	
		(*a*)	(*b*)
$10^{44\ 5}$–$10^{45\ 5}$	$0\ 8\times10^{-9}$	$1\ 8\times10^{6}$	$0\ 5\times10^{6}$
$10^{43\ 5}$–$10^{44\ 5}$	$1\ 6\times10^{-8}$	$1\ 8\times10^{7}$	$1\ 0\times10^{7}$
$10^{42\ 5}$–$10^{43\ 5}$	$3\ 3\times10^{-7}$	$1\ 8\times10^{8}$	$2\ 0\times10^{8}$
$10^{41\ 5}$–$10^{42\ 5}$	$6\ 6\times10^{-6}$	$1\ 8\times10^{9}$	$4\ 0\times10^{9}$

V. DISCUSSION

The lifetimes of around 10^9 years or more that we have found for the radio galaxies are rather longer than had been generally considered until now. It is hard to see how the present statistical approach could yield an entirely wrong result, unless the lifetime of the elliptical galaxies and of the brightest cluster galaxies is not around 10^{10} years. Although doubts have been expressed about the age of clusters of galaxies in connection with their stability (see Ambartsumian 1961), and about that of the first-ranked cluster galaxies (Morgan and Lesh 1965), there are no indications that bright elliptical galaxies in the field are much younger than 10^{10} years. If it were to be shown that they are indeed less old than 10^{10} years, then the derived lifetimes of the radio sources would be reduced correspondingly.

The first spiral galaxy associated with a strong radio source has just been reported recently (Sandage 1966). The present derivation of lifetimes of strong radio sources applies strictly only to those identified with elliptical galaxies.

It may be pointed out again that the lifetimes derived in this paper are all *total* lifetimes. The present statistical approach cannot distinguish between one radio stage of 10^9 years, or 10 radio events each lasting 10^8 years, etc.

This work was originally started with the purpose of obtaining lifetimes for quasi-stellar radio sources. The harmonic-mean lifetime was found to be around 10^6 to 10^7 years. The main uncertainty here is whether the quasi-stellar sources are related to radio galaxies at all.

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