1967MNRAS.136..123R

Mon. Not. R. astr. Soc. (1967) **136**, 123–140.

A POSSIBLE METHOD FOR INVESTIGATING THE EVOLUTION OF RADIO GALAXIES

Sir Martin Ryle and M. S. Longair

(Received 1966 December 29)

Summary

A method is suggested for determining the velocity of ejection and the ages of the components of double radio sources.

The derived variation of the radio luminosity with time suggests that nearly all extra-galactic radio sources, including the most compact quasi-stellar sources and the most extensive double radio galaxies, can be accounted for by a single model in which clouds of relativistic particles are ejected from the parent galaxy with an initial velocity close to *c*.

This type of variation of radio luminosity with time may be derived independently from the luminosity distribution of radio galaxies.

The cloud velocity and the radio luminosity both decrease to a small value after $\sim 3\times 10^6$ years. The decrease of luminosity exhibits two main phases, and suggests that all classes of powerful source originate with the release of energetic particles having a total energy of $\sim 10^{62}$ erg, in a galaxy containing a weak magnetic field ($\leqslant 10^{-5}$ gauss). The expansion from an extremely compact object exhibiting the effects of low-frequency self-absorption, must be accompanied by amplification of the magnetic field at the expense of the particle energy, and equipartition may be attained after $\sim 2\times 10^5$ years, when the physical separation of the components is approximately equal to the diameter of the galaxy.

The subsequent development, corresponding to the most extensive double sources, involves a rapid decrease of radio luminosity with age as the expansion proceeds without field amplification.

1. *Introduction.* The problems of accounting for the radio emission from radio galaxies and quasars have been discussed by many authors (e.g. Hoyle 1960, Shklovsky 1960, Burbidge, Burbidge & Sandage 1963). No alternative to the synchrotron emission mechanism has been discovered, and the observed intensities and spectra have allowed deductions to be made concerning the magnetic field and the numbers and energy spectra of the electrons responsible for the emission. The total energy required is least when there is approximate equipartition between the particle energy and the magnetic field energy (Burbidge 1959). Under these conditions, or those in which the magnetic field energy is greater, the rate of loss of energy due to radiation is so great that unless there is a continuing supply of energetic electrons, the emission will decrease in periods of $\sim 10^6$ years. If, on the other hand, the magnetic field is comparatively weak, the velocity of expansion of each component of a radio source will be determined by the amount of material within the expanding cloud and with energies of $\sim 10^{60}$ erg and masses of $\sim 10^8\ M_\odot$, these velocities are becoming significantly relativistic. From the angular sizes of the components of powerful sources, this again implies lifetimes of 10^6 years or less.

In some cases it is probable that a continuing source of electrons exists; the structure of Centaurus A (Bolton & Clark 1960, Maltby 1961) and of 3C 66, 129, 452 and 465 (Ryle, Elsmore & Neville 1965b, Macdonald, Ryle & Neville 1966) indicates that a series of events can occur and suggests that some source life-times are considerably greater than those associated with the decay of an individual plasma cloud. These sources, however, involve a relatively small total energy release, and are of comparatively small luminosity; these and similar sources may account for the longer life-times of $\sim 10^9$ years derived by Schmidt (1966) from a consideration of the relative local population densities of radio galaxies and the brightest members of clusters. In the case of the most intense radio galaxies and quasi-stellar sources, in which a single, very large release of energy seems to occur, a life-time much greater than $\sim 10^6$ years does not appear possible.

Many of the most powerful sources consist of two components disposed on either side of the parent Galaxy (Maltby & Moffet 1962) which suggests that the radio components are ejected from the nuclei of radio galaxies following some 'violent event'. The physical separations are so great that with component life-times of $\sim 10^6$ years the velocity with which the two components are ejected must be comparable with the speed of light. Significant changes in the emission may occur during the transition from a compact source to those as extensive as Cygnus A or 3C 47. Any information which could be obtained on the velocity of ejection of the components and on the way in which the total emission and other characteristics of the radiation from each component varied during this transition would be of great importance in understanding the mechanisms involved.

The possibility of high ejection velocities suggests a way in which this problem might be investigated, because unless the axis of the system is perpendicular to the line of sight, the two components will be observed at significantly different ages. A model based on this concept is described in Section 2, and is applied to a number of sources whose structure is known in some detail. The results suggest that the model may apply to a large proportion of these sources and hence other sources whose structure is known in less detail are also examined in the light of the same model.

2. *The source model.* A simple source model will be assumed, which supposes that two identical components are ejected from the parent galaxy with equal and opposite relative velocities v along a straight line which makes an angle ϕ with the line of sight in the frame of reference of the galaxy. It will initially be assumed that the velocity remains constant, although it is evident that interaction with the surrounding medium may eventually cause retardation.

It will be supposed that the radio galaxy is observed at a time t_0 (in the frame of reference of the galaxy) after the initial ejection. The more distant, receding, component will then be observed at an age t_1, in the frame of reference of the galaxy, where

$$t_1\left(1+\frac{v\cos\phi}{c}\right)=t_0.$$

This relationship is true even for $v/c \approx 1$. Similarly the nearer, approaching, component will be observed at a later stage of development t_2 where

$$t_2\left(1-\frac{v\cos\phi}{c}\right)=t_0.$$

Thus

$$t_1\left(1+\frac{v\cos\phi}{c}\right)=t_2\left(1-\frac{v\cos\phi}{c}\right)=t_0. \tag{1}$$

It is also evident that a remote observer will find the angular distances between the two components and the parent galaxy to be different; these will be given by:

$$\theta_1 = \frac{t_1 v \sin \phi}{R}; \quad \theta_2 = \frac{t_2 v \sin \phi}{R} \tag{2}$$

where R is the distance; at large distances the usual corrections for red-shift must be included.

For sources in which the position and red-shift of the parent galaxy is available from optical observations, θ_1, θ_2 and R are known; from the relative values of θ_1 and θ_2, the ratio t_1/t_2 is known, and hence from (1) $v \cos \phi/c$ can be determined.

In order to proceed further it is now necessary to assume a value of ϕ, and since there is an equal probability of ϕ lying in the ranges 0–60° and 60–90° a value of $\phi = 60°$ will be assumed in the remaining discussion. In a few of the sources considered in Section 3, it is probable that extreme values of ϕ occur, but it will be seen that the effect of an incorrectly assumed value is generally not of great importance in the final curves, and is unlikely to introduce errors much greater than those due to uncertainties in other properties of the sources.

For $\phi = 60°$, and from the observed values of θ_1, θ_2 and the distance R derived from the red-shift we can determine from (1) and (2) the quantities v/c, t_0, T_1 and T_2, where T_1 and T_2 are the ages of each component in its rest frame of reference; they are related to t_1 and t_2 by

$$t_i = \frac{T_i}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}} \quad (i = 1, 2).$$

If, as assumed, the two components are identical, we are therefore able to determine (i) the velocity of ejection, (ii) the age of the source (t_0) and from a measurement of the flux densities of the two components, (iii) the intrinsic luminosity P of each component and hence its rate of change at this age.

For (iii) it is necessary to correct the observed flux densities of the components for the effects of the Doppler shift due to the radial component of the velocity of ejection since this velocity may be close to that of light.

Denoting the red-shift of a plasma cloud measured by a distant observer due to its radial component of velocity by z',

$$1 + z' = \frac{1 \pm \frac{v}{c} \cos \phi}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}} \tag{3}^*$$

where the plus and minus signs refer to the receding (z_1') and approaching (z_2') components respectively. The observed intensities of the two components, S_1,S_2 at the observing frequency are related to the intrinsic luminosities P_1,P_2 at this frequency at proper times T_1 and T_2 by the relationship

$$S_i = \frac{P_i}{R^2(1 + z_i')^{1+\alpha_i}(1 + z)^{1+\alpha_i}} \quad (i = 1, 2)$$

---

* More precisely, the instantaneous velocities at t_1 and t_2 should be employed; it is assumed that these are close to the mean velocity during the expansion.

where $\alpha_1 \alpha_2$ are the spectral indices of the components at T_1 and T_2 and z is the cosmological redshift of the radio galaxy: R is the distance between the source and the observer in the frame of reference of the moving component and is related to the cosmological distance of the radio galaxy R_0 in the frame of reference of the observer by

$$R = R_0(1 + z_i')$$

Hence

$$S_i = \frac{P_i}{R_0^2(1 + z_i')^{3+\alpha_i}(1 + z)^{1+\alpha_i}} \quad (i = 1, 2) \qquad (4)^*$$

If α_1 and α_2 can be determined separately, the evolutionary changes in spectral index of these sources may be studied directly. For most sources, however, high resolution observations are only available over a limited range of frequencies and only the mean spectral index is known.

3. *The application of the method.* The analysis described above has been applied to a number of sources for which reasonably detailed observations are available; in general the method requires the accurate positions of the two components of a double source to be known relative to the optical object with which the initial release of energy can be associated. In many cases where the overall angular extent of the source is small, and especially where the optical object lies nearly symmetrically between the two components positional accuracies of $\sim 1''$ arc are necessary. The relative intensities of the two components on at least one frequency must also be available, as must the average spectral index, over the relevant frequency range. For these reasons the total number of sources available for study is at present limited, and most of them are the more extensive sources, which on the present model are those of comparatively greater age.

A number of such sources have been observed recently at a frequency of 1407 Mc/s with the one-mile telescope at Cambridge (Ryle, Elsmore & Neville 1965a, b, Macdonald, Ryle & Neville 1966 and Macdonald, Kenderdine & Neville 1967). The details of these sources are given in Table I. In several cases only tentative identifications have been made and red-shift measurements are not available. The approximate distances have in these cases been estimated from the apparent optical magnitude, assuming values of $M_{pg} = -20 \cdot 5$ for galaxies and -25 for star-like objects which are blue in colour. In a few cases the sources were associated with galaxies containing a compact blue nucleus, similar to the N-galaxies (Matthews, Morgan & Schmidt 1964); such galaxies are brighter than those associated with most radio sources, and an intermediate value of $M_{pg} = -22$ has been adopted.

Table I includes details of the probable identifications, the flux density, the angular separation of each component from the optical object and the angular diameter of each component; S_1, θ_1, ω_1 correspond to the component nearest to the optical object.

(a) *The interpretation of the data.* The projected physical separations of the two components from the optical object, corrected for the red-shift, $R\theta_1/(1 + z)$, $R\theta_2/(1 + z)$ for each of these sources are assembled in Table II. Using these data,

---

* A similar relationship has been derived by Faulkner, Gunn & Peterson (1966) in relation to the ratio of the numbers of red and blue shifts expected if quasi-stellar sources are ejected relativistically from nearby galaxies.

TABLE I

Source	Identification		z	S_1	S_2	θ_1	θ_2	ω_1	ω_2
				($\times 10^{-26}$ w.m^{-2} (c/s)$^{-1}$)					
3C 33	DE4 Galaxy	(a)	0·06	9·7	3·3	109″	135″	⩽15″	24″
47	QSS		0·425	2·4	1·3	24″	38″	⩽10″	18″
103	2 faint red objects close to axis of source: $m_{pg} \sim 18\cdot5$	(b)	(0·2)	3·6	1·9	35″	55″	*12″	<10″
109	N galaxy	(c)	0·306	1·9	2·3	44″	37″·5	22″	20″
219	CD5 galaxy	(a)	0·175	4·3	4·0	66″	69″	*24″	29″
223·1	DE4 galaxy	(d)	(0·065)	1·1	0·8	21″	50″	20″	16″
250	Red galaxy: $m_{pg} \sim 19$	(e)	(0·25)	0·68	0·63	13″	34″	<10″	<10″
252	Red galaxies: $m_{pg} \sim 20$	(f)	(0·3)	0·4	0·8	15″	36″	14″	<10″
313	Red galaxy: $m_{pg} \sim 20\cdot5$	(d)	(0·34)	2·0	1·5	44″	88″	12″	14″
332	N? galaxy: $m_{pg} \sim 18$	(b)	(0·3)	1·1	1·4	16″·5	42″	*20″	23″
340	Red stellar object: $m_{pg} \sim 18\cdot7$	(d)	(0·19)	1·65	0·75	3″·2	31″	<10″	<15″
356	Blue N-galaxy? $m_{pg} \sim 15\cdot3$	(g)	(0·2)	1·0	0·52	32″·5	36″·5	<10″	<10″
381	Red galaxies: $m_{pg} \sim 17\cdot5$	(d) (g)	(0·13)	2·5	1·3	29″·5	30″·5	16″	25″
390·3	N galaxy	(g)	0·056	7·8	3·0	101″	167″	*<10″	20″
Cygnus A	CD3 galaxy		0·057	765	635	40″·3	54″·7	20″	25″

(a) Schmidt (1965)
(b) Macdonald, Ryle & Neville (1967)
(c) Sandage, reported by Wyndham (1966)
(d) Veron (1966)
(e) Wills & Parker (1966)
(f) E. A. Parker (private communication)
(g) Wyndham (1966)

* Bridge of radio emission joins the two components. (Macdonald, Kenderdine & Neville (1967)).

the relationships given in Section 2 have been used to derive the values of the ejection velocity (v/c) and the ages of optical and radio components t_0, T_1 and T_2. The Einstein–de Sitter world model has been adopted in these computations, with $H = 100$ km s^{-1} Mpc^{-1}.

TABLE II

Source	$\frac{R\theta_1}{1+z}$ ($\times 10^3$ l.y.)	$\frac{R\theta_2}{1+z}$	$\frac{v}{c}$	t_0 ($\times 10^3$ years)	T_1	T_2	α	P_1 (w(c/s)$^{-1}$ ster^{-1})	P_2	
3C 33	291	360	0·21	1730	1535	1900	0·66	$4{\cdot}64 \times 10^{24}$	$7{\cdot}6 \times 10^{23}$	
47	275	435	0·45	865	621	999	0·97	$1{\cdot}44 \times 10^{26}$	$1{\cdot}2 \times 10^{25}$	
103	256	388	0·41	875	660	1000	0·77	$3{\cdot}4 \times 10^{25}$	$3{\cdot}8 \times 10^{24}$	
109	357	421	0·16	2760	2520	2990	0·76	$2{\cdot}1 \times 10^{25}$	$1{\cdot}5 \times 10^{25}$	
219	445	465	0·13	3660	3510	3680	0·74	$1{\cdot}3 \times 10^{25}$	$1{\cdot}0 \times 10^{25}$	$\phi = 80°$
223·1	60	144	0·47	360	266	539	0·56	$2{\cdot}0 \times 10^{25}$	$6{\cdot}6 \times 10^{22}$	$\phi = 30°$
250	109	285	0·89	202	64	168	1·02	$3{\cdot}9 \times 10^{26}$	$7{\cdot}3 \times 10^{24}$	
252	135	335	0·86	258	92	230	1·10	$2{\cdot}3 \times 10^{26}$	$1{\cdot}1 \times 10^{25}$	
313	442	870	0·65	1050	600	1180	0·86	$1{\cdot}7 \times 10^{26}$	$9{\cdot}4 \times 10^{24}$	
332	155	395	0·87	294	102	256	0·67	$4{\cdot}2 \times 10^{26}$	$1{\cdot}8 \times 10^{25}$	
340	23	222	0·94	89	17	162	0·71	$1{\cdot}3 \times 10^{27}$	$1{\cdot}2 \times 10^{25}$	$\phi = 30°$
356	236	266	0·12	2470	2300	2600	0·97	$4{\cdot}3 \times 10^{24}$	$1{\cdot}5 \times 10^{24}$	
381	156	161	0·09	1700	1670	1730	0·66	$3{\cdot}7 \times 10^{24}$	$1{\cdot}8 \times 10^{24}$	$\phi = 80°$
390·3	252	417	0·49	738	515	853	0·64	$7{\cdot}5 \times 10^{24}$	$4{\cdot}7 \times 10^{23}$	
Cygnus A	102	138	0·173	700	600	810	0·75	$3{\cdot}4 \times 10^{26}$	$9{\cdot}0 \times 10^{25}$	$\phi = 30°$
			0·30	452	375	505		$4{\cdot}1 \times 10^{26}$	$1{\cdot}1 \times 10^{26}$	$\phi = 60°$
			0·86	139	62	84		$3{\cdot}3 \times 10^{27}$	$8{\cdot}6 \times 10^{26}$	$\phi = 80°$

In most cases it has been assumed that ϕ, the angle between the axis of symmetry of the source and the line of sight, is 60°. Of the fifteen sources studied, it is to be expected, on the basis of a random orientation, that three will have $\phi < 30°$ and three will have $\phi > 80°$. In one case (3C 340) the derived value of the radial component of velocity is so great that ϕ must be less than 60° and a value of 30° has been adopted; the same value has also been taken for 3C 223.1. In two other cases (3C 219, 381) a rather small value of v/c and correspondingly large values of t_0, T_1 and T_2 result from assuming $\phi = 60°$, and a value of $\phi = 80°$ has been adopted which leads to a model consistent with the other sources. In all four cases the sources are so marked in Table II. In order to illustrate the effect of errors in the adopted value of ϕ, the result of using values of $\phi = 30°$, 60° and 80° are given for Cygnus A.

The final columns of Table II give the derived values of P_1, P_2 the intrinsic radio luminosities of the two components at times T_1 and T_2 for a frequency of emission of 1407 Mc/s. These values have been corrected for the expansion velocity and for the cosmological red-shift using equation (4).

The data of Table II are also presented in Figs. 1 and 2, which show the variation of v/c with t_0 and the values of P_1, P_2 as a function of T. The components of each source are joined in the latter figure to show the change of radio emission with age. It should be noted that Fig. 1 implies that the velocity of the components of a double radio source decreases with time and therefore the ages of the components derived on the basis of constant velocities will be slightly in error. This, however, will only introduce a small error in the ages tabulated in Table II.

1967MNRAS.136..123R

(b) *Compact sources.* The results presented in Figs. 1 and 2 show that the powerful sources which have been shown to consist of two components having angular separations $>20''$ arc are in reasonably good agreement with the source model proposed in Section 2. The results suggest that the initial expansion velocity is very great and decreases to a value of $\sim 0{\cdot}1c$ after a period of 3×10^6 years.

It is therefore of interest to extend the analysis to other sources which have physical extents less than those given in Table II. For many of these sources it is impossible to establish the relative positions of the two components and the optical object with sufficient accuracy to allow the full analysis to be carried out since the component separations are less than $20''$ arc. It is however interesting to estimate where such sources would lie in Fig. 2. By comparing the projected linear separations (which lie in the range $50\text{–}200\times10^3$ l.y.) with those of the sources listed in Table II, approximate velocities of expansion of $v/c \sim 0{\cdot}4$ may be derived. Estimates of the ages and luminosities for the two components may then be made using the same procedure described in Section 2 since once v/c is known, all the parameters of the model are defined. The data have been derived from the observations of Allen, Palmer & Rowson (1960) for 3C 295 and Clark & Hogg (1966) for 3C 245, 254, 270·1 and 459. Data on the dimensions of their components have been taken from Clark & Hogg and from the measurements of interplanetary scintillation of Hewish, Scott & Wills (1964). The sources are listed in Table III and are shown in Fig. 2 with dashed lines.

It can be seen from Fig. 1 that for even more compact sources the values of v/c are likely to approach unity and from equation (4) this results in a large ratio in the observed flux densities of the two components. For example, with $v/c=0{\cdot}9$, $\phi=60^\circ$ and $\alpha=0{\cdot}75$, the relative ages of the two components will be in the ratio of 3 : 1 and for comparable emitted powers, the observed intensities would be in the ratio 40 : 1. It is thus possible that in many such sources, the observations will not reveal the presence of the receding component (apparently younger) unless its power is very much greater than that of the approaching component (apparently older). In fact, from equations (1) and (4) it can be seen that on this model if an

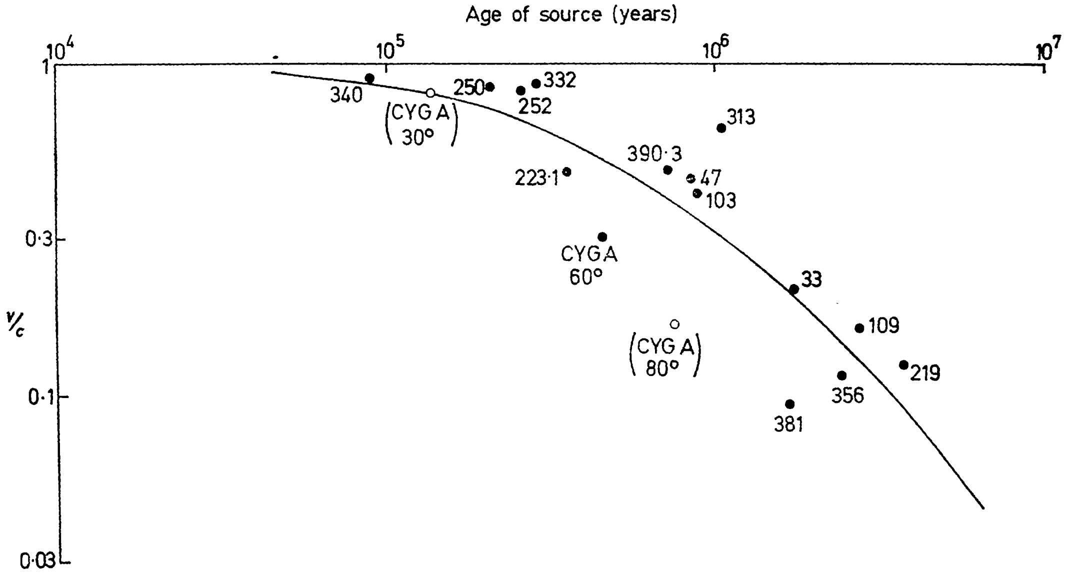

FIG. 1. *The velocity of the plasma clouds as a function of time. Cygnus A is shown for assumed angles between the axis of ejection and the line of sight of* 30°, 60° *and* 80°.

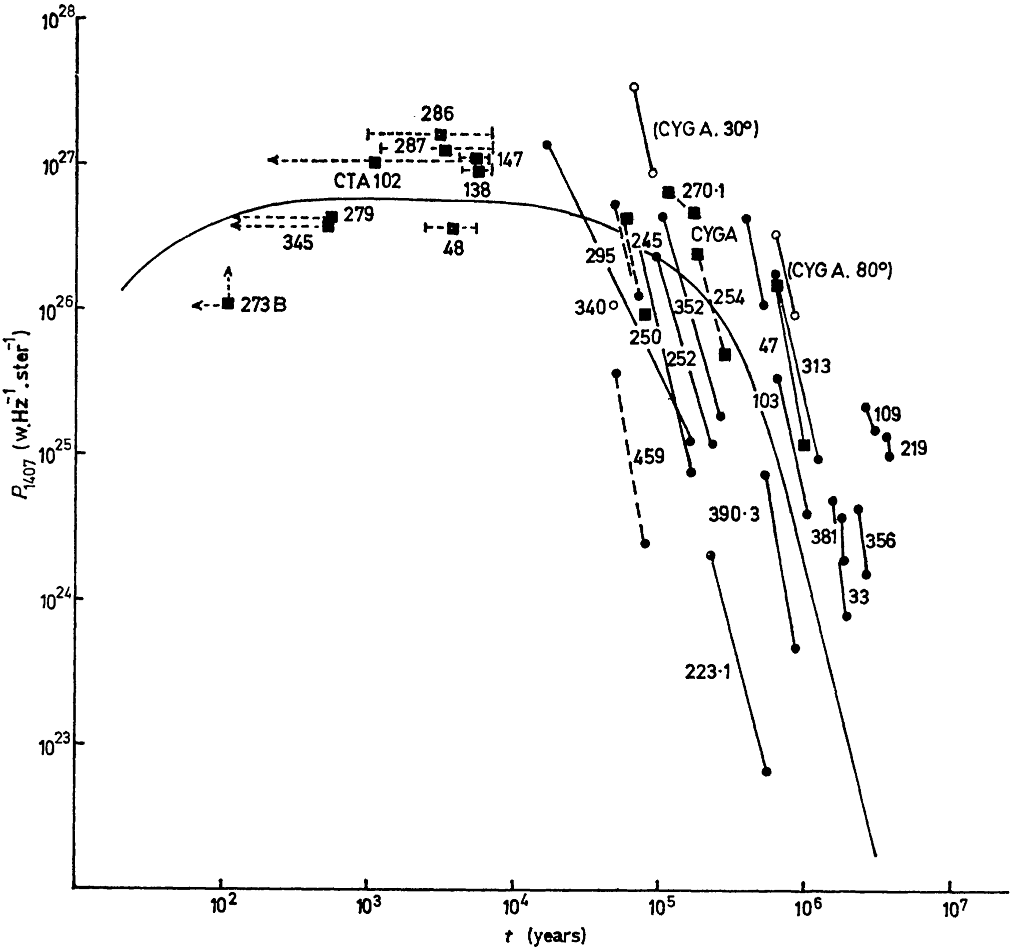

FIG. 2. *The evolution of radio galaxies derived from the radio sources discussed in Section* 3.

●, *component of radio galaxy;*

■, *component of quasi-stellar source.*

The double source components listed in Table II are joined by thick lines, those in Table III by dashed lines and the limits to the ages of the quasi-stellar sources by dotted lines. The thin curve will be taken to represent the evolutionary behaviour of a typical radio galaxy at a frequency of 1407 *Mc/s. Cygnus A is shown three times to illustrate the effect of changing the angle between the axis of ejection and the line of sight.*

equal double source ($S_1 = S_2$) is observed, then, the component luminosity must be decreasing rapidly with age as $P \propto t^{-(3+\alpha)}$. Even with the rapid evolution implied by the double sources plotted in Fig. 2, it is unlikely that the receding component will be observed in sources having $v/c > 0 \cdot 9$.

The most compact sources observed may therefore represent only a single component of a double source, the flux density of the receding component being reduced so much that its presence is difficult to establish.

On this model it is, however, still possible to establish the power of the approaching component and to set upper and lower limits on its age. The discrepancy between the optical and radio positions allows an upper limit of θ_2 to be derived and hence to T_2. A difficulty arises due to the use of many of these sources as calibrators in the most accurate observations (Adgie 1964, Adgie & Gent 1965), but when a number of calibrators has been used to determine the instrumental constants, a useful upper limit to θ_2 may still be derived. For many of these sources, a lower limit to the age may also be obtained from their angular extent (Anderson *et al.* 1965, Adgie *et al.* 1966) which when corrected in the manner indicated by equation (5) (see Section 3(e) below) allows a lower limit to the age T_2 to be derived. These limits are presented for a number of sources in Table IV and are included in Fig. 2. It is likely that CTA 102 is younger than most of the sources listed in Table IV since it exhibits self-absorption effects at high frequencies.

TABLE III

Source	z	$\frac{v}{c}$	t_0	T_1	T_2	α	P_1	P_2	Approximate component size
			($\times 10^3$ l.y.)				(w (c/s)$^{-1}$ ster^{-1})		($\times 10^3$ l.y.)
3C 245	1·03	0·4	68	51	71	0·71	$4{\cdot}3\times10^{26}$	$9{\cdot}3\times10^{25}$	9
254	0·74	0·4	240	183	274	0·91	$2{\cdot}3\times10^{26}$	$5\ \ \times10^{25}$	61
270·1	1·5	0·4	145	110	165	0·75	$6{\cdot}2\times10^{26}$	$4{\cdot}4\times10^{26}$	38
295	0·46	0·4	63	47	71	0·61	$5{\cdot}4\times10^{26}$	$1{\cdot}2\times10^{26}$	25
459	0·22	0·4	65	49	74	0·87	$3{\cdot}6\times10^{25}$	$2{\cdot}5\times10^{24}$	5

TABLE IV

Source	z	Angular diameter	Radio-optical position	Minimum age ($\times 10^3$ years)	Maximum age ($\times 10^3$ years)	P_{1407} (w (c/s)$^{-1}$ ster^{-1})
48	0·37	0″·4	<1″	2·4	5·3	$3{\cdot}6\times10^{26}$
138	0·759	0″·5	<1″	4·6	7·0	$9{\cdot}0\times10^{26}$
147	0·55	0″·6	<1″	4·3	6·4	$1{\cdot}1\times10^{27}$
286	0·85	0″·12	<1″	1·0	7·3	$1{\cdot}5\times10^{27}$
287	1·06	0″·14	<1″	1·2	7·4	$1{\cdot}3\times10^{27}$
CTA 102	1·04	<0″·1	<1″	<0·8	7·4	$1{\cdot}0\times10^{27}$

A number of sources which show variability in their radio emission (Dent 1965, Kellermann & Pauliny-Toth 1966) may be associated with even younger objects. These sources (3C 273B, 279, 345) are also included in Fig. 2. It should be noted that the two components of 3C 273, for which much detailed information is available (Hazard, Mackey & Shimmins 1963, Bailey *et al.* 1964, Hughes 1965) cannot be explained by a single event because of the almost perfect coincidence between the radio and optical components of source B, suggesting that as in the case of other complex sources (e.g. 3C 129, 452 and 465) a second release of energy has taken place. Because of its radio variations and its peculiar spectrum, which suggest that powerful self-absorption mechanisms are present, an upper limit of 100 years has been adopted for the age of 3C 273B.

The evidence presented in Fig. 2 suggests that most of the sources studied so far can be associated with a fairly well defined evolutionary sequence; this model includes the most compact sources known, which appear to have ages of $\sim 10^3$ years and the most extensive double sources with an age of $\sim 3\times10^6$ years. The considerable overlap between sources showing the characteristics of quasi-stellar sources (indicated by square symbols in Fig. 2) and radio galaxies suggests that no distinction should be drawn between them.

Perhaps the most important feature of the results shown in Fig. 2 is the marked change at $t \sim 10^5$ years. For $10^3 < t < 10^5$ years the variation of P is small but for $t > 10^5$ years, the luminosity decreases rapidly with age.

(c) *Selection effects.* It is important to examine the possibility that the apparent evolutionary path derived in Fig. 2 has been influenced by the way in which sources lying in different parts of the figure have been selected. Ideally, the curve should be based on a complete sample of sources selected, for example, by a limiting flux density or red-shift, but this is not possible because of the instrumental limitations discussed in the previous section; as a result, the sample is not complete for $T < 3 \times 10^4$ years, although the arguments presented in Section 3(b) have permitted estimates of the ages of quasi-stellar sources of small angular size to be made.

Sources showing a more complex structure which suggest a series of less powerful releases of energy, have not been considered at all, since they clearly cannot be interpreted in the present simple model. Their radio luminosities are generally considerably less than those discussed here.

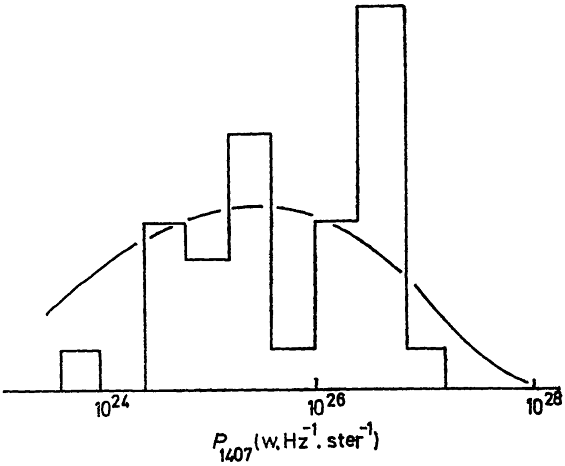

FIG. 3. *The luminosity distribution of the radio sources used in the analysis and plotted in Fig. 2 compared with the luminosity distribution of Longair & Scott* (1965).

A comparison of the distribution of radio luminosity of the sources included in Fig. 2 with the luminosity distribution of Longair & Scott (1965) (Fig. 3) shows that apart from an excess of quasi-stellar sources and the deficiency of weak sources expected, the sample does not appear to be significantly different from that of a sample selected down to a limiting flux density.

A further complication does however arise from the fact that the most powerfu sources in the sample have large red-shifts and the effects of cosmological evolution cannot be neglected. Corrections for this effect can be deduced from the analysi of cosmological evolution already presented by Longair (1966) which shows th variation with cosmological epoch of source luminosity needed to account for th observed number–flux density relationship.

The model evolutionary path is therefore indicated by the thin line in Fig. which is intended to represent the evolution of sources at the present epoch.

(d) *The luminosity distribution.* An entirely independent check of the mod *P–t* curve shown in Fig. 2 may be derived from considerations of the luminosit distribution of radio galaxies. If a class of radio sources is formed at a ra n_0 Mpc^{-1} year^{-1} and they all follow the same evolutionary path, then the luminosi function $\rho(P)$ (Longair & Scott 1965) of these radio galaxies due to their evolution is given by

$$\rho(P) = \frac{n_0}{\left(\frac{dP}{dT}\right)_P}$$

Thus it is possible to derive $\rho(P)dP$ and hence $n(P)dP$, the luminosity distribution, for different model evolutionary paths. Fig. 4(a) illustrates three such model curves, model (i) being similar to the model evolutionary path derived in Fig. 2. The resulting $n(P)$ distributions are compared with the luminosity distribution of Longair & Scott in Fig. 4(b).

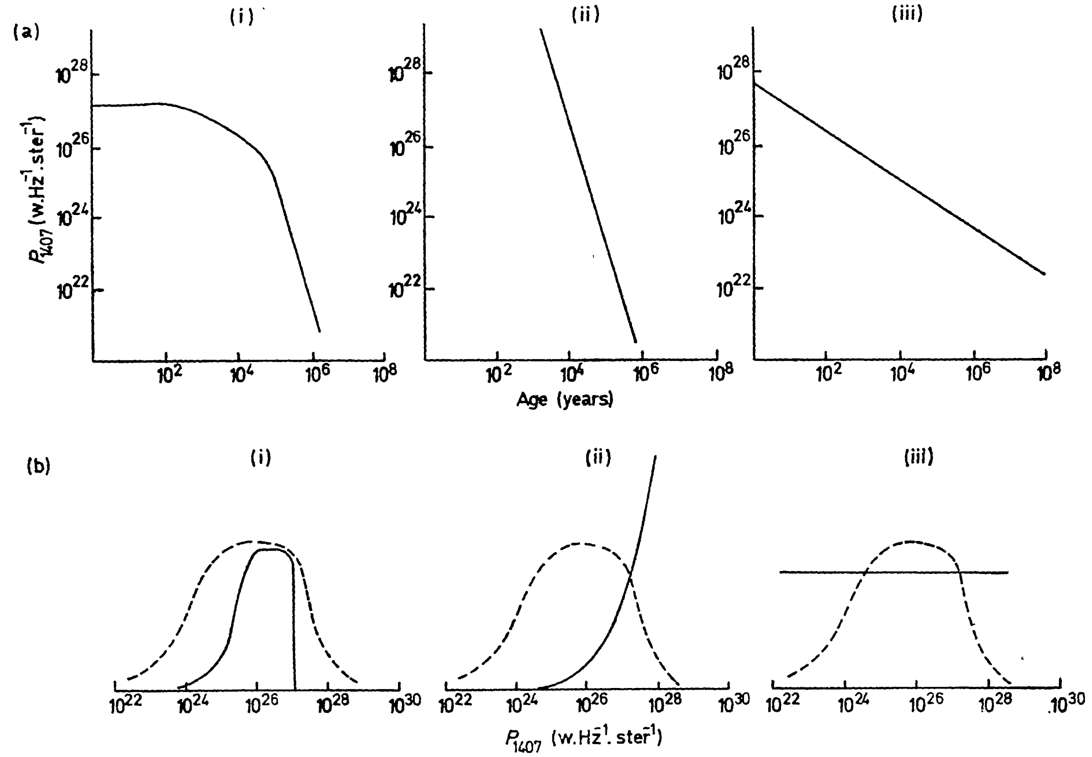

FIG. 4. *Model P–t evolutionary paths (a) and the corresponding luminosity distributions (b). Model (i) when broadened by a factor of* 10^2 *due to the dispersion of sources about the mean evolutionary track is in good agreement with the luminosity distribution of Longair & Scott* (1965) *which is indicated by the dashed line.*

If account is taken of the dispersion in the properties of radio galaxies about the model evolutionary path of $\sim 10^2$, then model (i) is in excellent agreement with the observed luminosity distribution. In model (ii) which represents a continuously decreasing luminosity having a rapid decay ($P\alpha t^{-3}$), sources are observed preferentially at their maximum luminosity and hence if such an evolution occurred in extended sources such as 3C 47, some exceedingly powerful radio galaxies would be expected at a given flux density—these are not observed. In model (iii), the luminosity decreases less rapidly ($P\alpha t^{-2/3}$) and results in a flat luminosity distribution. In this case, the radio sky would be populated with many low luminosity radio galaxies and quasi-stellar sources having very large component separations. Such sources are not observed in a complete sample of sources brighter than a given flux density.

It is therefore clear that there must be two distinct phases in the evolution of a radio galaxy into an extended double source. A maximum luminosity is first attained and then the luminosity decays rapidly. Sources are observed preferentially during their period of maximum luminosity. This type of evolution is entirely consistent with the model P–t behaviour derived from Fig. 2.

(e) *The component size.* Before discussing the results presented in Figs. 1 and 2, it is important to investigate the way in which the linear dimensions of the components themselves vary with time. The results are only of limited accuracy, firstly because, due to inadequate resolving power, the observational evidence is less complete than that describing the positions of the components, and secondly because the model may be oversimplified—for example, no account has been taken of the presence of ‘ bridges ’ between the two components which are found in a number of the sources described in Table I.

In most cases for which detailed evidence is available, it is found that the extent along the axis of the source is greater than that in a perpendicular direction; under these circumstances the angular extent along the projected axis may be used to derive the physical extent along the axis except for sources in which ϕ is small.

In deriving the physical extent for a given value of ϕ it is necessary to correct the observed values of angular extent to take account of both the expansion velocity v, and the cosmological redshift. Owing to the radial component of the expansion velocity, the receding component appears smaller and the approaching component appears larger by factors of

$$\frac{1 \pm \frac{v}{c}\cos\phi}{\left(1-\frac{v^2}{c^2}\right)^{1/2}}.$$

For measured angular sizes (along the projected axis) of ω_1 and ω_2 these corrections lead to physical dimensions along the source axis which are given by:

$$R\frac{\omega}{\sin\phi}\frac{\left(1 \pm \frac{v}{c}\cos\phi\right)}{\left(1-\frac{v^2}{c^2}\right)^{1/2}}\frac{1}{(1+z)}, \tag{5}$$

the plus and minus signs referring to the receding and approaching components respectively. In the case of the compact sources listed in Table III information is only available in the form of a possible model in which the components are supposed to have the same angular size. The results for the sources listed in Tables II, III and IV are all shown in Fig. 5 together with the curve showing the physical separation of the component from the optical source which may be derived from Fig. 1.

The large scatter and the presence of components with an apparent expansion velocity greater than c are partly due to the use of a mean value of T_1 or T_2 as the age at which the whole of the component is observed. For sources having a large value of v/c the corrections are sufficiently great to require a more precise treatment, although this is hardly justified with the present simple model and incomplete observations.

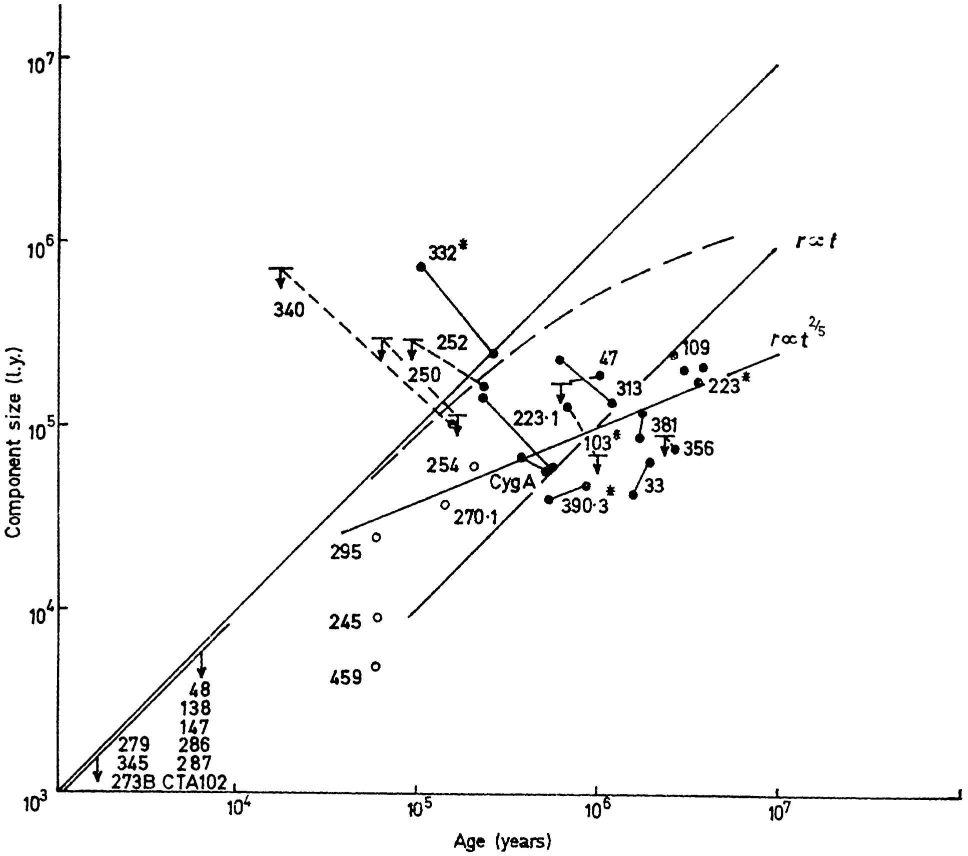

Fig. 5. *The dimensions of the individual source components as a function of time. The circles represent the sources listed in Table III. Sources with a ' bridge ' between the two components are marked with an asterisk. The dashed curve shows the separation of the components as a function of time. The straight lines describe* $r \propto T^{2/5}$ *and* $r \propto T$.

Despite the considerable scatter, it seems clear that a large increase in the physical scale must occur during the period $10^3 < T < 10^5$ years, since for small values of T the component sizes must lie below the full curve corresponding to the component separation. If the relative extents along and perpendicular to the axis of expansion remain the same throughout this period, then it can be seen from Fig. 5 that the volume of each component must increase by a factor of $\sim 10^4$ during the period $10^3 < T < 10^5$ years.

4. *The source model—the physical processes.* The results presented in the preceding sections have suggested that both powerful radio galaxies and quasi-stellar sources follow the same evolutionary path. Furthermore, sources having $3 \times 10^4 < T < 3 \times 10^5$ in Fig. 2 (but not those of other ages) exhibit the characteristics of both classes of source, a result which strongly suggests that the quasi-stellar sources represent a stage through which all powerful radio sources pass.

The violent event which is responsible for the release of vast amounts of energy in the form of relativistic particles may also enhance the emission at optical wavelengths resulting in a superluminous nucleus ($M_{pg} \sim -25$) with a star-like appearance. The intense optical emission will normally make the detection of the ' galaxy ' itself impossible. It is however interesting to note that there is now definite evidence for a faint diffuse nebulosity around the stellar nucleus of 3C 48

(Sandage & Miller 1966). It is thus plausible to suppose quasi-stellar sources are powerful radio galaxies at early stages in their evolution, although in some cases such as 3C 47, 245 and 270·1, the superluminous stage may last for periods up to 10^6 years. In the source model, it is therefore assumed that the evolution of a powerful radio galaxy is initiated by the sudden release of energy within the nucleus of the galaxy.

There are then three main stages to be considered in the subsequent evolution of the ejected clouds of relativistic particles:

(i) The earliest stages when the volume occupied by the plasma clouds does not greatly exceed that of the gas cloud responsible for the optical emission ($T < 10^3$ years).

(ii) The expansion of the plasma clouds at roughly constant luminosity ($10^3 < T < 10^5$ years).

(iii) The rapid decay in the radio emission ($T > 10^5$ years).

Stage (i) $T < 10^3$ *years*. During the early stages of the expansion, Williams (1966) has shown that the observed spectral curvature of quasi-stellar sources at low frequencies, implies that the energy is predominantly in the form of high energy particles and greatly exceeds that in the magnetic field. The origin of the relativistic particle energy (it will later be shown to be $\sim 10^{62}$ erg) is still a matter of much speculation and no detailed discussion of the many possible sources of energy will be given (for review, see Burbidge, Burbidge & Sandage 1963). Neither will any discussion be given of the mechanisms by which a radio source attains a double configuration. It is assumed that during this stage a large amount of energy is channelled into two clouds of relativistic particles which are ejected in opposite directions at relativistic velocities.

Stage (ii) $10^3 < T < 10^5$ *years*. It is interesting to note that after 10^5 years the separation of the radio components from their point of origin is roughly equal to the radius of a typical galaxy, suggesting that during the stage (ii) plasma clouds are passing through the interstellar medium. During this stage, the dimensions of the components, which must initially be less than 10^3 light years, attain a value of 3×10^4 l.y. at $T \sim 10^5$ years corresponding to an increase in volume by a factor of $\sim 10^4$. During this expansion the radio luminosity at 1407 Mc/s (P_{1407}) remains roughly constant, despite the adiabatic energy loss which each particle must suffer (Shklovsky 1960). This result cannot be attributed to the effects of diminishing self-absorption since spectral measurements show no absorption at such high frequencies. At low frequencies however, self absorption is of great importance and the corresponding curve drawn for a frequency of 38 Mc/s (P_{38}) shows that such effects persist until $\sim 3 \times 10^4$ years. The observed values of P_{38} normalized to the values of P_{1407} are shown in Fig. 6.

These results might be explained in two extreme ways:

(a) If magnetic flux is conserved, the field $H \propto 1/r^2$ where r is the radius of the plasma cloud. A continuing process of particle acceleration or injection must then take place if the radio emission is to be maintained despite the adiabatic losses in particle energy and field.

(b) If no further particle acceleration occurs, the magnetic field strength in the plasma cloud must *increase* during the expansion to compensate for the adiabatic energy loss of the electrons. This process will continue until equipartition between the magnetic field and relativistic particle energies is attained.

These two alternative possibilities may be distinguished by considering how P_{1407} and P_{38} would vary during the expansion. It will be supposed that the magnetic field varies with the radius of the plasma cloud as $H \propto r^{-\beta}$ and that the number of relativistic electrons varies as r^{δ}; in the latter case it will be assumed that the particles are injected with an electron energy spectrum which is the same as that of those originally present.

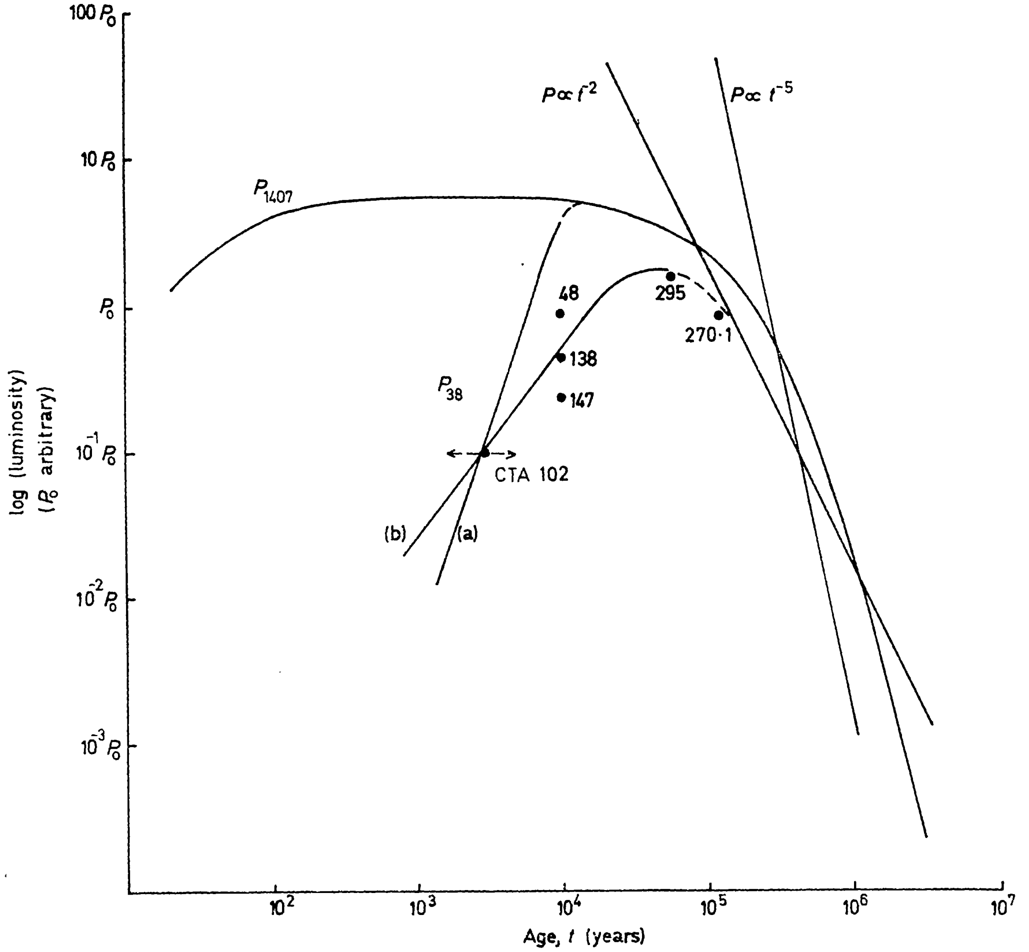

FIG. 6. *The luminosity at* 38 *Mc/s as a function of time.*
(*a*) *is the expected evolution if particles are continually injected for* $T < 10^5$ *years.*
(*b*) *is the expected evolution if the magnetic field increases during the period* $T < 10^5$ *years with no acceleration or injection of particles. For* $T > 10^5$ *years, the straight lines represent* $P_{1407} \propto T^{-2}$ *and* $P_{1407} \propto T^{-5}$.

If it is assumed that the cut-off in the radio spectrum occurs at some frequency between 38 and 1407 Mc/s as a result of synchrotron self-absorption, it is possible to calculate how the luminosity at these two frequencies depends upon the radius of the plasma cloud. It is assumed that above and below the cut-off frequency S

is proportional to $\nu^{-\alpha}$ and $\nu^{+2 \cdot 5}$ respectively. The variations of P_{1407} and P_{38} may now be written:

$$P_{1407} \propto r^{-2\alpha-\beta(\alpha+1)+\delta}$$

$$P_{38} \propto r^{2+\beta/2} \tag{6}$$

It will be assumed that $\alpha = 0 \cdot 75$.

For model (a) $\beta = 2$ and to provide a variation of P_{1407} comparable with that observed, it is necessary to adopt a value of $\delta \sim 5$. The variation of P_{38} corresponding to this model is shown in Fig. 6 where it is seen that the effects of the low frequency cut-off would only be apparent for sources of very small age. Furthermore, since the linear dimensions of the source increase by a factor of ~ 20, the total particle energy must, on this interpretation, increase by a factor of 3×10^6, and for values of the initial field comparable with those derived by Williams (1966) an electron energy of $\sim 10^{64}$ erg must be accepted. If the total particle energy is some 100 times that of the electrons (Burbidge 1959) then the total energy requirements of model (a) become 10^{66} erg, a figure comparable with the rest mass energy of a galaxy of $10^{11}\, M_\odot$.

In model (b) it is supposed that the magnetic-flux can be amplified and that $\delta = 0$; good agreement with the observed variations of both P_{1407} and P_{38} can then be obtained if it is assumed that $\beta = -1$. The predicted variation is shown in Fig. 6.

In both cases it should be noted that the dependence of P_{38} upon age has been evaluated on the assumption that the radio emission originates from a uniform homogeneous plasma cloud; the effects of inhomogeneities and gradients of magnetic field and particle density are to reduce the dependence of P_{38} upon age in both cases. It appears, however, that model (b) provides a better explanation of the observed variation of emitted power since it requires a very much smaller total energy.

Upper limits to the magnetic field in a typical radio galaxy for $T < 10^5$ years may be derived from the spectral cut-offs at low frequencies due to synchrotron self-absorption. For 3C 48, 147, 286 and 287, fields less than $1 \cdot 8 \times 10^{-4}$, 5×10^{-3}, 10^{-5} and 10^{-5} gauss are obtained respectively (Williams 1966) and the particle and field energies at different stages of the development of the sources may be derived. In order to produce the observed radio luminosity at 1407 Mc/s, the total electron energy for both components at $T \sim 10^3$ years is given by

$$E_e = 6 \times 10^{53}\, H^{-3/2} \text{ erg}$$

and for a field 5×10^{-5} gauss this amounts to 2×10^{60} erg corresponding to a total particle energy of 2×10^{62} erg (if the protons are supposed to represent 100 times the energy of the electrons). The field energy is very small by comparison at this early stage ($\sim 10^{54}$ erg).

At $T \sim 10^5$ years, the physical size has increased by a factor of ~ 20 and the magnetic field has increased $\sim 10^{-3}$ gauss, so that the total field energy is $\sim 4 \times 10^{60}$ erg; this figure is then comparable with the particle energy which has decreased by a factor of 20 as a result of the adiabatic losses.

It is concluded that the most satisfactory explanation of the roughly constant luminosity of radio galaxies during stage (ii) is that the magnetic field is amplified from an initial value of 10^{-5} gauss or less. An initial energy of $\sim 10^{62}$ erg is then required.

The mechanism by which the particle flux may produce such an increase in the magnetic field energy is not understood. It is interesting to note, however, that during stage (ii) the expansion takes place through the interstellar medium, suggesting that the magnetic field energy has been amplified as a result of interaction between the plasma clouds and the ambient medium. Kulsrud *et al.* (1965) have recently examined the related problem of the expansion into the interstellar medium of a plasma cloud resulting from a supernova explosion and have shown that a large amplification of the ambient field is possible for a highly supersonic expansion. The limiting value of the field is determined by the increase in particle pressure at the surface of the expanding cloud and occurs when the magnetic field energy $(H^2/8\pi) = 2\rho_0 v_0{}^2$ where v_0 is the velocity of expansion and ρ_0 the density of the ambient medium. In the case of expansion velocities of the order occurring in this model, this limitation does not arise for $H \leqslant 10^{-3}$ gauss.

Stage (*iii*) $T > 10^5$ *years*. There are two ways in which the amplification of the magnetic field will eventually be limited. (a) If equipartition is not reached, the plasma clouds may pass from the interstellar medium into the much lower density of the intergalactic medium—or, (b) equipartition between the magnetic field and the particle energies may be attained and further increase in the magnetic field can no longer take place. In either case, the plasma cloud will continue to expand maintaining the same relative energy densities of field and particles, since both decrease as r^{-4}. The luminosity will then decrease according to equation (6) with $\delta = 0$ and $\beta = 2$, corresponding to $P \propto r^{-5}$ if $\alpha = 0{\cdot}75$.

In the present model both effects are likely to become important after $\sim 10^5$ years, since the physical separation of the plasma clouds then correspond to galactic dimensions, and with the magnetic fields suggested in the previous section equipartition will also be approached.

If the plasma cloud expands at constant velocity then $r \alpha T$. If, on the other hand, the cloud is decelerated by the surrounding medium then it can be shown (see e.g. Sedov (1959)) that $r \alpha T^{2/5}$. These two possibilities are drawn on Fig. 6; no distinction between them can be made with the present data.

In both cases, it is clear that the rapid decrease in radio luminosity suggested by Fig. 2 will occur after $\sim 10^5$ years, with $P \alpha T^{-5}$ in the first case and $P \alpha T^{-2}$ in the second.

5. *Conclusion*. It has been shown how the characteristics of a large proportion of powerful extra-galactic radio sources may be explained in terms of a simple model in which clouds of energetic particles are ejected at relativistic velocities from the centre of a galaxy. No distinction is made between quasi-stellar sources and radio galaxies; it is indicated how both may represent different stages in one evolutionary sequence. It has already been suggested that quasi-stellar radio sources occur in elliptical galaxies in the process of formation (Field 1964). According to the proposed model the sudden release of relativistic particles with a total energy of 10^{62} erg can explain the spectra, radio luminosity and luminosity distribution of both quasi-stellar and double radio galaxies. The more complex sources of lower luminosity seem to require a series of less powerful events.

The development of the model depends on the density both of the interstellar medium in the galaxy where the energy is released, and of the intergalactic medium. It is therefore evident that the evolution of a radio source will be different at different cosmological epochs.

We are grateful to a number of our colleagues both for valuable discussions and for providing us with observational data in advance of publication, especially Dr. A. C. Neville and Mr G. H. Macdonald. One of us (M. S. L.) gratefully acknowledges a Sir James Clerk Maxwell Scholarship.

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
Cambridge.
1966 *December.*

References

Adgie, R. L., 1964. *Nature, Lond.*, **204,** 1028.
Adgie, R. L. & Gent, H., 1966. *Nature, Lond.*, **209,** 549.
Adgie, R. L., Gent, H., Slee, O. B., Frost, A. D., Palmer, H. P. & Rowson, B., 1965. *Nature, Lond.*, **208,** 275.
Allen, L. R., Palmer, H. P. & Rowson, B., 1960. *Nature, Lond.*, **188,** 731.
Anderson, B., Donaldson, W., Palmer, H. P. & Rowson, B., 1965. *Nature, Lond.*, **205,** 375.
Bailey, J. A., Branson, N. J. B. A., Elsmore, B. & Scheuer, P. A. G., 1964. *Nature, Lond.*, **201,** 755.
Bolton, J. G. & Clark, B. G., 1960. *Publs astr. Soc. Pacif.*, **72,** 29.
Burbidge, G. R., 1959. *Paris Symposium on Radio Astronomy* (ed. by Bracewell), p. 541. Stanford University Press.
Burbidge, G. R., Burbidge, E. M. & Sandage, A. R., 1963. *Rev. mod. Phys.*, **35,** 947.
Clark, B. G. & Hogg, D., 1966. *Astrophys. J.*, **145,** 21.
Dent, W. A., 1965. *Science*, **148,** 1458.
Field, G. B., 1964. *Astrophys. J.*, **140,** 1434.
Faulkner, J., Gunn, J. E. & Peterson, B. A., 1966. *Nature, Lond.*, **211,** 502.
Hazard, C., Mackey, M. B. & Shimmins, A. J., 1963. *Nature, Lond.*, **197,** 1037.
Hewish, A., Scott, P. F. & Wills, D., 1964. *Nature, Lond.*, **203,** 1214.
Hoyle, F., 1960. *Mon. Not. R. astr. Soc.*, **120,** 338.
Hughes, M. P., 1965. *Nature, Lond.*, **207,** 178.
Kellermann, K. I. & Pauliny-Toth, I. I. K., 1966. Paper presented at Erevan Conference on Instability Phenomena in Galaxies.
Kenderdine, S., Ryle, M. & Pooley, G. G., 1966. *Mon. Not. R. astr. Soc.*, **134,** 189.
Kulsrud, R. M., Bernstein, I. R., Kruskal, M., Fanucci, J. & Ness, N., 1965. *Astrophys. J.*, **142,** 491.
Longair, M. S., 1966. *Mon. Not. R. astr. Soc.*, **133,** 421.
Longair, M. S. & Scott, P. F., 1965. *Mon. Not. R. astr. Soc.*, **130,** 379.
Macdonald, G., Neville, A. C. & Ryle, M., 1966. *Nature*, **211,** 1241.
Macdonald, G., Kenderdine, S. & Neville, A. C., 1967. (In preparation.)
Maltby, P., 1961. *Nature, Lond.*, **191,** 793.
Maltby, P. & Moffet, A. T., 1962. *Astrophys. J. Suppl. Ser.*, No. 67.
Matthews, T. A., Morgan, W. W. & Schmidt, M., 1964. *Astrophys. J.*, **140,** 35.
Ryle, M., Elsmore, B. & Neville, A. C., 1965*a*. *Nature, Lond.*, **205,** 1259.
Ryle, M., Elsmore, B. & Neville, A. C., 1965*b*. *Nature, Lond.*, **207,** 1024.
Sandage, A. R. & Miller, W. C., 1966. *Astrophys. J.*, **144,** 1238.
Schmidt, M., 1965. *Astrophys. J.*, **141,** 1.
Schmidt, M., 1966. *Astrophys. J.*, **146,** 7.
Sedov, L. I., 1959. *Similarity and Dimensional Methods in Mechanics*. Cleaver-Hume Press, London.
Shklovsky, I. S., 1960. *Cosmic Radio Waves*. Harvard University Press.
Veron, P., 1966. *Astrophys. J.*, **144,** 861.
Williams, P. J. S., 1966. *Nature, Lond.*, **210,** 285.
Wills, D. & Parker, E. A., 1965. *Mon. Not. R. astr. Soc.*, **131,** 503.
Wyndham, J. D., 1966. *Astrophys. J.*, **144,** 459.