AN ELECTRODYNAMIC MODEL OF RADIO GALAXIES AND QUASARS

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SUMMARY

It is shown by statistical and individual studies that the powerful radio sources exhibit increases in magnetic energy and flux by factors $\sim 10^2$--$10^3$ as sources age $10^3$--$10^5$ years. This requires a previously developed field system extending $> 100$ kpc along, and twisted around, the rotational axis.

Our model comprises a rotating gas cloud from which a galaxy condenses, and a pre-existing field which is amplified until the Rayleigh–Taylor instability causes ejection of magnetic tongues along the axis. In an old galaxy the gas has turned to stars (perhaps burnt out), to a corona and to a small central cloud.

This cloud, of mass $\sim 10^6 M_\odot$, radius $\sim 10^{16}$ cm, field $\sim 10^6$ gauss, rotates rapidly to provide the relativistic particles for the radio and optical synchrotron sources. Its thermal plasma provides the QSO line emission.

The electrodynamic-gravitational model thus accounts for the complex field system, the acceleration of particles over a period $\sim 10^5$ years, disposal of angular momentum, changes in luminosity, and line emission. Some tests of the model are proposed. In 'normal' galaxies the corresponding model is an oblique magnetic rotator which may account for the lower level of radio emission, for the phenomena in Seyfert galaxies and for cosmic rays in general and the primary cosmic rays in our Galaxy in particular.

I. INTRODUCTION

Radio galaxies and quasars originate with the ejection from the nucleus of the parent object of two clouds of relativistic electrons. The electrons move in magnetic fields to provide two radio-source components, each of which moves away with a velocity initially approaching that of light, usually expanding in the process. Energy requirements of some sources exceed $10^{50}$ erg and must be met by gravitational energy. However, models based on superstars fail to explain the continuous release of energy over long periods, while those based on dense clouds of stars fail to explain the disposal of angular momentum in elliptical galaxies.

The morphology and origin of the magnetic field system, usually ignored in theories of radio galaxies and quasars, imposes the most stringent restrictions of all on a source model. We shall see that this must have developed long before the electrons were injected, and must have systematic orientation throughout a volume much greater than that of the parent galaxy. Its energy is comparable with that of the electrons and so must surely have its origin in the same source of gravitational energy, some of which must be converted to magnetic energy before the remainder is transferred to the fast particles. The flux and morphology of the field cannot be accounted for by a galactic field or by a general intergalactic field.

We also consider below, the evolution of a source model, starting with a protogalaxy with a magnetic field orthogonal to the rotational axis. The radio source...
appears \( \gtrsim 10^{10} \) years later as relativistic electrons are released into a field which has developed during that period. A major change from earlier theory (Piddington 1964, 1966, 1967a, b) is the formation of a galactic corona by the Rayleigh–Taylor instability rather than by loss of equilibrium of the whole central region. A major addition is a magnetic rotator to provide the cosmic rays (as in pulsar theory) and also, perhaps, to explain the line emission of the QSOs.

Slightly modified (oblique field) magnetic rotators in spiral galaxies are proposed as the source of most cosmic radiation including the primary radiation in our Galaxy.

2. INTERPRETATION OF RADIO AND OPTICAL DATA

Studies of radio brightness distribution of various sources indicate that these evolve by the emission from a parent optical object of two clouds of relativistic electrons which move in opposite directions and expand (Moffet 1966). Again, a plot of luminosity against surface brightness (Shklovskii 1962; Aizu et al. 1964; Heeschen 1966), shown schematically in Fig. 1, reveals a well-defined ‘main sequence’ common to radio galaxies and quasars. Although this common evolutionary sequence is accepted here, it is not essential to the conclusions reached or model developed. A second source sequence is provided by the spiral and irregular galaxies; this and the random plots are discussed in Section 5.

Since, in general, one component moves away from and one towards the observer, they must have attained different ages in a system fixed in the parent galaxy. This enabled Ryle & Longair (1967) to determine source ages and component velocities. The resulting age scale (applying only to the main sequence) has been added to Fig. 1. Initial velocities are close to that of light and fall to \( \sim 0.1 \) c.

![Fig. 1. A schematic representation of earlier plots of radio source luminosity against brightness showing a ‘main sequence’ of quasars and radio galaxies and an independent arm of ‘normal’ galaxies. The age scale refers only to the main-sequence sources. A few misfits are marked with squares; these are spirals or irregulars of unusual brightness and may evolve as shown by the dashed line. Optical luminosities are shown for comparison.](image-url)
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Young sources show fluctuations within a year and so have dimensions \( \gtrsim 10^{18} \) cm; up to \( \sim 10^8 \) years they increase in luminosity, probably because of decreasing self absorption. The remarkable feature of the plot is the maintenance of constant luminosity for the period \( 10^3 - 10^5 \) years while the size is increasing by a factor \( \sim 20 \).

2.1 Interpretation

Luminosity and brightness depend on the energies of the particles \( (W_p) \) and field \( (W_m) \) and on the component radius \( R \). It is convenient to define \( W_m \) and the magnetic flux \( \psi \) of the large-scale field \( B \) as

\[
W_m = \frac{1}{8} B^2 R^3 \quad \psi = BR^2.
\]

Here we attempt to show that as a source ages from \( 10^3 \) to \( 10^5 \) years, the values of \( W_m \) and \( \psi \) increase by factors of perhaps \( 10^3 \) and \( 10^2 \) respectively; there must also be a large increase in \( W_p \).

In Shklovskii's (1960) original 'plasmoid' or closed system of particles and fields, adiabatic expansion causes both \( W_m \) and \( W_p \) to decrease as \( R^{-1} \) so that, in the absence of self-absorption, luminosity decreases as \( L \propto R^{-2\gamma} \), where \( \gamma \) is the spectral index of the electrons. The large, bright sources have total energies \( > 10^{60} \) erg and as Moffet (1966) has pointed out, plasmoids with this energy must, at an earlier stage, have been enormously more luminous than any known object and must have contained inexplicably large amounts of energy. The main sequence of Fig. 1 shows an increase in \( R \) by a factor \( \sim 20 \) with no decrease in \( L \). For double sources \( \gamma \) has a value \( \sim 2.4 \), which means that for a plasmoid \( L \) would decrease by a factor \( > 10^6 \). Thus the components are not plasmoids, but receive fresh particles or fresh field energy or both.

Early evidence of self-absorption in compact sources suggested large excesses of particle energy which led Ryle and Longair to conclude that \( W_m \) alone increased, the factor being \( > 10^6 \). More recent measurements indicate little or no excess of particle energy in compact sources, and from these Kellerman & Pauliny-Toth (1969) have concluded that \( \psi \) is conserved so that \( B \propto R^{-2} \).

There appear to be sound physical arguments against each of these conclusions. It seems that both \( W_m \) and \( W_p \) must increase, the former by the invasion of pre-existing magnetic flux tubes situated outside the parent object. Increase of magnetic energy alone is physically implausible as it would require the original electrons to move outwards into regions of stronger field and larger flux. Even if such a magnetic configuration were possible, the electrons could not invade the region of stronger field (because of conservation of magnetic moment) or larger flux (because of inability to move across field lines with velocity \( \sim c \)). There appear to be equally conclusive arguments against an increase in particle energy only. Initially \( W_p \) equals or slightly exceeds \( W_m \) and would require an increase by a factor \( > 10^6 \). The inevitable result would be that the components would explode. With the centres of the explosions only \( \gtrsim 10 \) kpc from the centre of the galaxy, the components would combine to form one more or less spherical source. An explanation of the average source, having two components with separation four times their individual size, implies control of the particles by the field and so comparable energy densities even in the older sources. This argument applies equally if an intergalactic gas-field system is invoked to explain the retardation of component expansion. On the other hand, if some vaguely conceived 'galactic field' is invoked, as in some theories,
then this must extend well beyond the galaxy and a suitable field is found to have just the characteristics of our model field. These arguments are expanded in the following subsection.

To explain the small, widely separated source components, such as those of 3C33 with a ratio ~ 20, even more rigorous magnetic control is required and an excess of magnetic energy to confine and guide the electron clouds. Some alternative theories invoke inertial or gravitational forces in small but massive clouds of thermal plasma and relativistic particles ejected like bullets from the parent galaxy. Apart from the apparent lack of a plausible ejection mechanism, these models fail to explain the brightness distribution or polarization of the larger source components and are unacceptable as models of most sources.

Further evidence of an increase in $\psi$ is provided by polarization changes discussed below. Meanwhile we conclude that while ageing from $10^3$ to $10^5$ years $R$ increases by a factor ~ 20, $W_m$ and $W_p$ by factors ~ $10^5$ and $\psi$ (given by equations (1)) by a factor ~ 100.

2.2 Model field systems

The model for a radio source magnetic field system proposed here is similar to an earlier system (Piddington 1966) except for its mode of formation. It is shown schematically and in an early stage of development in Fig. 2. The large elliptical figure represents a section of a massive ($\sim 10^{10} M_\odot$) gas cloud rotating about the axis $\omega$ and winding up the intergalactic field $B_0$ (originally $\lesssim 10^{-9}$ gauss). Such a field must be invoked to explain fields observed in most galaxies, and as differential rotation is general in galaxies, a spiral field with alternate layers in opposite directions must form as shown. A tongue of field $B_e$ has been ejected by the Rayleigh–Taylor instability as described below and it is envisaged that in due course relativistic

![Fig. 2. An intergalactic magnetic field $B_0$ orthogonal to the galactic rotational axis $\omega_0$ is wound into a spiral field $B_\sigma$. Magnetic tongues erupt on either side of the galaxy (only one shown) along the rotational axis to form a field system similar to those in the radio sources. Synchrotron emission commences with the injection of fast electrons and is polarized as shown.](https://academic.oup.com/mnras/article-abstract/148/2/131/2601534/b6equisi on 28 January 2019)
electrons are released into this tongue to move away from the gas cloud with velocity \( \sim c \) and to provide the synchrotron emission.

The whole external field system is, of course, much more complex than that of Fig. 2. It comprises many tongues, ejected by the Rayleigh–Taylor instability, inflated with cosmic-ray gas and twisted together by galactic rotation as described in Section 3. Some of the field lines pass through the galactic nucleus and some through the disc. The cosmic-ray accelerator (Section 4) is a magnetic rotator at the centre of the galaxy. It causes violent hydromagnetic disturbances which travel outwards across the central part of the galaxy. These disturbances accelerate cosmic rays which move outwards along the field lines, first invading those lines which pass through the nucleus. Later, some electrons are released into field lines which do not traverse the nucleus, and as these, together with the early electrons, spread along their respective field lines they increase the magnetic energy of the synchrotron source. The magnetic energy of the whole system cannot, of course, increase appreciably during the brief period (\( \sim 10^5-10^6 \) yr) available.

Implicit in most theories of radio galaxies and quasars is a field system somehow formed by the expanding cloud of relativistic gas from a ‘galactic’ or an ‘extra-galactic’ field whose structures are not defined. Such theories fail in several ways. Since the relativistic particles dominate and amplify the field they will develop a spherical form and a shell source as in the well-known models of radio sources in supernova remnants. Such models require an excessively strong intergalactic field and one must then ask why this was not wound up. Finally they fail to explain observed polarization changes described below.

We conclude that a field system of the type shown in Fig. 2 exists prior to the appearance of a radio source. The first electrons to be released from the central region move nearly along the axis \( \psi \) and the inferred increases in \( W_m \) and \( \psi \) could not occur if the fresh electrons, represented by the increase in \( W_p \), were released into these original flux tubes. Some increase in \( W_m \) would result from a spread of particles along the flux tubes, but unless the increase is limited to \( \lesssim 10 \) this would result in a long thin component. In any case, the increase in \( \psi \) requires the invasion of fresh flux tubes from the galactic central region. A further clue to the field structure is the observed change of polarization vector as sources age. The change and its explanation by Gardner & Whiteoak (1966) are illustrated by the E vectors of electrons \( X \) and \( Y \) in Fig. 2. This may be a little oversimplified, and Morris & Whiteoak (1968) suggest that twisting of the field lines during source evolution may be the cause. As seen below, there can be little twisting of the field during the relatively brief lifetime of the sources. However, there must be a great deal of twisting prior to the source appearance and it is found that field lines more distant from the rotational axis are likely to be more twisted. Since these outer lines are last to be filled with electrons, the change of polarization is thus accounted for.

A model field system must also account for the isolation of most components from the optical parent. This simply requires the field lines close outside the galaxy to form tongues as in Fig. 2. Particles tend to be trapped near the tips of the tongues and their outward motion slowed; they are also prevented from returning to the parent by the stronger field in that region. The isolated components will eventually expand and the emission decay.

As a basis for a quantitative model, we consider two stages in the evolution of a large, luminous component in which \( W_m \sim W_p \) and the particles are assumed mainly electrons. Some typical values (Bridle 1967; Malby, Matthews & Moffet 1963 and
For a small source are

\[ R = 0.3 \text{ kpc}, \quad B = 10^{-3} \text{ gauss}, \quad W_m = 10^{56} \text{ erg}, \quad \psi = 10^{58} \text{ gauss cm}^2. \]

For the older source

\[ R = 30 \text{ kpc}, \quad B = 3 \times 10^{-5} \text{ gauss}, \quad W_m = 10^{59} \text{ erg}, \quad \psi = 3 \times 10^{41} \text{ gauss cm}^2. \]

Apart from our neglect of a possible large amount of proton energy, these models represent maximum requirements of power and flux in the synchrotron source. As the field extends well beyond the source, the total field energy will be several times larger again, about \( 10^{60} \text{ erg} \).

Summing up the requirements of a source field, the flux must exceed the value expected for a 'galactic field' by a factor \( \geq 100 \) and the lines must converge and pass through the central region. The energy is comparable with that of the particles, but could not have been provided by the particles. Presumably it resulted from conversion of gravitational energy in the same massive object which provides the particle energy, but during an earlier stage of contraction. It will be seen in Section 4 that the convergence of field lines into the central system is also a requirement of the optical synchrotron source.

### 3. The Hydromagnetic Evolutionary Phase

Differential rotation and a frozen-in magnetic field appear to be characteristics of galaxies in general, and must lead inevitably to field amplification and the conversion of gravitational energy to rotational kinetic energy and magnetic energy (Piddington 1966, 1967a). Here we shall show that when the field has a substantial component orthogonal to the rotational axis, a spiral field develops followed by a field generally similar to that of Fig. 2.

In a cylindrical system of axes \( r, \phi, z \), the rotational vector \( \omega(r) \) lies along the \( z \) axis and the field develops as

\[ \frac{\partial B_\phi}{\partial t} = -rB_r \frac{\partial \omega}{\partial r}. \tag{2} \]

The plasma experiences an electromagnetic force whose important component is given by

\[ f_\phi = \frac{B_r}{4\pi r} \frac{\partial}{\partial r} (rB_\phi). \tag{3} \]

This magnetic amplification and orbital acceleration are the basis of the model developed here.

#### 3.1 Gravitational to magnetic and kinetic energy

Near the rotational axis the product \( rB_\phi \) must be increasing with \( r \) and so the force is a braking force. Far from the centre \( B_\phi \to 0 \) and so \( rB_\phi \) must decrease with \( r \) and the force must be an accelerating force. We are mainly concerned with the part of the galactic plasma which is braked, loses angular momentum, shrinks to lower Kepler orbits and so converts gravitational energy to kinetic energy of rotation and to magnetic energy provided by winding and compressing the original field. In our Galaxy \( B_\phi \sim 10^3 B_r \) after about \( 10^{10} \) years; thus the effect is likely to be important, but only after a substantial period of time.
The dynamics of elliptical galaxies are not understood, let alone their evolution from primeval gas, so that we may trace the development of the field only in a very general way. We start with a more or less spherical system $M = 10^{12} M_\odot$, $R = 30$ kpc, $B = 10^{-8}$ gauss. This is the cloud which is braked and which contracts, and in which the field first develops. As it contracts it sheds stars which disconnect from the field, maintain large orbital dimensions and so define a large optical galaxy of type E. The field is compressed by the contracting cloud, whose mass is decreasing, perhaps to only 1 per cent or so of its original mass. The gravitational energy which has been released at radius $R(t)$ is

$$\Omega \sim G(M + M_\odot)^2 R^{-1},$$

where $G$ is the gravitational constant and $M_\odot$ is an 'equivalent mass' of stars. During a particular short interval the contribution $\delta \Omega$ to $\Omega$ is determined by the shrinkage of a mass $M(t)$ of gas in the field of the gas cloud and stars within the gas cloud. The total energy is found by integrating, and may be represented by an equivalent mass which is a fraction of the total mass of stars.

Let us consider the evolving cloud at a rather late stage when it has shrunk to one per cent of the galactic radius and, say, one per cent of the total mass. Then we have $R = 300$ pc, $M = 10^{10} M_\odot$, $\Omega \sim 3 \times 10^{58}$ erg if the effects of stars are ignored, or more if these are considered. At this stage its angular velocity $\omega = (GM/R^3)^{1/2}$ is $4 \times 10^{-14}$ s$^{-1}$. As a result of compression of the frozen-in field $B_r$ increases to $10^{-4}$ gauss while differential rotation tends to increase $B_\phi$ to a much greater value, certainly more than $10^{-3}$ gauss which corresponds to $W_m \sim 10^{56}$ erg as required by our small source model. However, the model meets a difficulty in that it tends to collapse to a small disc and may then fragment. Some method of support of the gas cloud in the $z$ direction seems to be necessary, not only at the above rather late stage but throughout much of its life. The problem relates to that of the spheroidal star systems of some E galaxies.

Suppose that the cloud does form a disc, or oblate spheroid, flat enough to apply the one-dimensional equation of hydrostatic support

$$\frac{d}{dz} (P + p + B^2/8\pi) = -\rho(z) g(z),$$

where $P$ and $p$ are the gas and cosmic-ray pressures, $\rho$ the gas density and $g$ the gravitational acceleration perpendicular to the disc. First consider the possibility of support by magnetic pressure alone using a simple model

$$\rho = \rho_0 \exp(-z/h), \quad B = B_0 \exp(-z/h),$$

where $\rho_0$, $B_0$ are the values in the galactic plane $z = 0$ and $h$ is the scale height. The field needed for support is independent of the value of $h$ and is given by $B_0^2 \sim 4GM^2R^{-4}$ which is approximately the value given by the scalar virial equation $W_m \sim \Omega$ after using equations (1) and (4) and is the field needed to support a uniform spherical cloud. In our model $B_0 \sim 10^{-3}$ gauss which is so strong that it brakes the disc or sphere to rest within one radian, thus demonstrating that the development of such a strong field by differential rotation is not possible. There is little chance of support of the cloud by gas or cosmic-ray pressures but the difficulty may be resolved by the intervention of the Rayleigh–Taylor instability.
3.2 Rayleigh–Taylor instability

Parker (1966, 1967) has shown that the type of equilibrium described by equation (5) may be unstable to transverse hydromagnetic waves. The gas flows into pockets suspended in the field, while loops of field, freed from gas, erupt away from the disc. This is a form of the Rayleigh–Taylor instability. In the case of a gas cloud contracting to an E galaxy, the gas is only partially supported and inertial effects must be important. Nevertheless it seems likely that the same instability will be present and that pockets of dense gas must form and move towards the galactic plane while loops of field with tenuous gas erupt outwards.

The phenomenon is shown schematically in Fig. 3 where a gaseous disc contains a fast-rotating nucleus $N$ which winds up a field $B$ into oppositely directed spiral segments $B_1$ and $B_2$ separated by a spiral neutral sheet. If a small section $X$ of a magnetic rope rises above the general level, then gas flows along the field lines down towards the galactic plane where it compresses the field. Meanwhile the section $X$ erupts to form a magnetic tongue or loop, carrying with it a residue of gas. This phenomenon appears to be an inevitable result of continuous field winding and may be in evidence in M82, in our Galaxy and perhaps in some solar eruptive prominences.
Parker’s analysis provides a criterion of instability which, neglecting cosmic-ray pressure, depends on the ratio $B^2/P$ and on the constant $\gamma$ in the equation of state $\delta P/P = \gamma (\delta n/n)$. The value of $(\gamma - 1)$ is likely to be small, $\geq 0.2$, in which case eruptions occur when $B^2/8\pi n \lesssim 0.4P$. The pressure is given by $P = \mu u^2$, where $u$ is the total random gas velocity in the $z$ direction. If the gas cloud has $M = 10^{11} M_\odot$, $R = 3$ kpc, thickness $= 1$ kpc, then $\rho \sim 2 \times 10^{-22}$ g cm$^{-3}$ and for $u = 10-100$ km s$^{-1}$ we have instability when $B \gtrsim 4 \times 10^{-5} - 4 \times 10^{-4}$ gauss. Since winding and compression are capable of developing stronger fields than these we conclude that a coronal field such as that shown by the loops $B_y$ in Fig. 3 is likely to form.

The instability and its attendant kinetic effects may also explain how a gaseous mass could exist for a long period without collapsing to a very thin disc. Clumps of gas falling towards the galactic plane will become highly condensed and so tend to form stars which will disconnect from the field (Spitzer 1969) and fall right through the plane to take up orbits with large $z$ components. These stars will carry away much of the inward momentum, but prior to their formation they transferred some outward momentum to the more tenuous clouds of erupting gas. This magnetic ‘seesaw’ may thus account in part for support of the gas cloud. Additional support must be given by the field system which develops as a galactic corona. Part of the energy of this system must be included in the virial equation or, from another point of view, the loops of magnetic field which close within the galaxy will provide additional support for the gas against gravitational collapse. Conversely, as seen below, the gas provides an anchor for the external field system and helps prevent it from expanding and dissipating its energy and flux.

3.3 The external field system

The external field system begins to develop from the intergalactic field $B_0$ as the latter is pinched into an hourglass form by the contracting pre-galaxy. Its strength at this stage need only be $\sim 10^{-8}$ gauss, but is increased by galactic rotation and twisting of the field lines about the rotational axis. This field is represented by the lines $B_y$ in Fig. 4. Magnetic neutral sheets will form between field lines directed inwards to the galaxy and those directed outwards, and some loops may disconnect from the intergalactic field as shown by the field $B_y'$. Later the magnetic tongues $B_z$ (Fig. 3) emerge along the rotational axis and develop twists around this axis as shown in Fig. 4. The pitch angle of the more or less helical twist depends on the ratio of the velocity of the galactic gas to the Alfvén velocity outside the galaxy. The latter depends on the plasma density which might lie somewhere between that of the original cloud ($\sim 6 \times 10^{-25}$ g cm$^{-3}$) and that found between galaxies in a cluster ($\sim 5 \times 10^{-28}$ g cm$^{-3}$). The corresponding range of Alfvén velocities for $B = 10^{-6}$ gauss is $\sim 4-130$ km s$^{-1}$ and with peak rotational velocities $\sim 400$ km s$^{-1}$ there is likely to be considerable winding. Near the axis, the rotational velocity is small, there is negligible winding and the field lines lie parallel with the axis. Further away from the axis the field is twisted and so compresses the central field; the whole system develops partial force-free characteristics.

Some insight into the characteristics of such a field is provided by a simple, cylindrical model having only components $B_\phi(r)$ and $B_z(r)$ in our cylindrical axes. The most important force-free condition is $f_r = \sigma$, or

$$\frac{\partial}{\partial r} (B_\phi^2 + B_z^2) + \frac{r}{2} B_\phi^2 = \sigma, \quad (7)$$
which shows that $B_{\phi}(0) = 0$ and that the total intensity $(B_{\phi}^2 + B_z^2)^{1/2}$ decreases steadily as $r$ increases. For a uniform helical twist $B_{\phi} = \alpha r B_z$, where $\alpha$ is a constant representing the degree of twisting. Then (7) may be solved to give
\begin{equation}
B_{\phi} = B_0 \alpha r \{1 + (\alpha r)^2\}^{-1}; \quad B_z = B_0 \{1 + (\alpha r)^2\}^{-1},
\end{equation}
where $B_0 = B_z(0)$. If $\alpha r = 1$ at say 1 kpc from the axis and $B_0 = 10^{-5}$ gauss, then when $r = 100$ kpc $B_{\phi} = 10^{-7}$ gauss and $B_z = 10^{-9}$ gauss.

This field system seems to satisfy the general requirements of the radio source field determined earlier. An important feature is the large flux, which is invariant in an expanding or contracting system and so must be accounted for either by winding as above or by assuming an improbably powerful intergalactic field. The field strength and flux in the original cloud need only be $10^{-8}$ gauss and $10^{38}$ gauss cm$^2$, and as the latter amount is added every quarter revolution, the requirement of $\lesssim 10^{41}$ gauss cm$^2$ is easily met. Another requirement is restraint of the field against its tendency to expand into intergalactic space. According to the virial theorem $W_m < \Omega$ and reference to equations (1) and (4) shows that mass $M \sim 10^3 \psi$ is required to anchor a field of given flux. This mass is $\lesssim 10^{11} M_\odot$, which is far greater than that of the gas available in an old elliptical galaxy and so incapable of maintaining a static situation.

**Fig. 4. The form of the magnetic field required to explain the radio source data, and also the field which evolves naturally from that shown in Figs 2 and 3. The original intergalactic field $B_0$ is pinched ($B_{\phi}$) and some lines reconnect across a neutral sheet ($B_{\phi}'$). These and the coronal field $B_c$ are all twisted by galactic rotation; finally, a cloud of cosmic-ray electrons is released from the galactic central region.**

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The answer to this apparent difficulty is that the system is not static but is expanding away from the galaxy while fresh flux is generated up to the time when the cosmic rays appear. The largely force-free form of the field provides a negative outward gradient of field strength which at several hundred kiloparsecs may reduce it almost to the level of the general field and so require little expansion.

4. THE SYNCHROTRON EVOLUTIONARY PHASE

With the appearance of a cloud of relativistic electrons at the centre of the galaxy, the above magnetic field system becomes a synchrotron source model. The electrons move away from the centre, mainly along the magnetic field lines which are shown (on one side only) in Fig. 4. They first invade lines nearest the rotational axis and, since these are not twisted, twin components emerge with velocity $\sim c$. Other electrons invade field lines further from the rotational axis and emerge more slowly because the lines are twisted. Most important, invasion of these fresh lines accounts for the inferred increase in magnetic flux and energy; only a developed field system may do so.

The model seems to account for the other features of the radio sources, notably the systematic orientation of the field system over large distances and its large energy which must have derived from gravitational energy released near the galactic centre. When magnetic energy density dominates, the cosmic-ray gas will be controlled and guided. Depending on the field structure in a particular source, the components may be small and widely separated as for 3C 33, or elongated along the axis as in 3C 76.1, 3C 452, 3C 284 and others surveyed by Macdonald, Kenderdine & Neville (1968), or complex as in Cygnus A. On the other hand, when the particle and magnetic energy densities are comparable, the components tend to be circular and closely spaced as for Forman A, 3C 47, 3C 69 and others.

Particles moving outward along field lines will generate hydromagnetic waves and these in turn will tend to scatter the particles (Wentzel 1969, where earlier references are given). This will reduce the outward bulk motion below the velocity of light, and will also stretch and elongate the force tubes. Later arriving particles contribute to the elongation but eventually the supply dwindles. After scattering, some particles start to move back towards the galaxy, but as they enter regions of stronger field they are reflected and trapped near the ends of the tongues to provide two isolated components.

An important requirement of the model is that cosmic rays are accelerated over a period $\sim 10^5$ years rather than in a single explosive event. In fact, there is even some evidence that the rate of increase of energy itself increases as the source ages. The evolutionary data show constant luminosity as size increases by a factor $\sim 20$ and the source ages from $10^8$ to $10^5$ years. This seems to require increases of both $W_p$ and $W_m$ by factors $\sim 10^8$ while the age increases by a factor of only $10^5$ in which case the rate of energy injection must increase after $10^8$ years.

Whether or not the rate of increase of $W_m$ itself increases, there is little doubt that $W_m$ increases by a large amount and that this requires a pre-existing field. Finally, the model explains the observed changes in source polarization. In young sources most electrons are confined to the vicinity of the axis where the field is along the axis; in older sources electrons have invaded the region of twisted lines where $B_\phi$ predominates as shown by equation (8).
4.1 The source of relativistic particles

The energy of the relativistic particles of the radio sources is so great that it must also have a gravitational origin. This must be in the same gas cloud that, earlier, powered the field and through which the field lines pass, as otherwise the particles would not be injected into the field. The relationship is also necessary to magnetically brake the cloud and so make its gravitational energy available. Furthermore, the particle acceleration mechanism must be electromagnetic rather than by stellar explosions. One reason is that stars will have disconnected themselves from the magnetic field system so that the particles are excluded from the field. Another reason is the inefficiency of a 'supernova' event in providing particles of energy \( \sim 10^8 \) eV. Protons of this energy and total energy \( 10^{60} \) erg have a rest mass of only \( \sim 10^6 M_\odot \) which is only a tiny fraction of the mass involved in the explosions, most of whose energy appears in sub-relativistic particles.

At first sight it might seem that the Rayleigh–Taylor eruptions might provide the acceleration, but this cannot be so. Some particles may gain relativistic energies in shocks but the great majority attain hydromagnetic velocities and energies smaller by \( \gtrsim 10^4 \). Furthermore, the eruptions occur over a long period (comparable with the age of the galaxy) while the synchrotron electrons are all injected within \( \sim 10^5 \) years indicating a much more violent phenomenon.

A model which appears to satisfy the requirements is the magnetic rotator or spinning plasma cloud with an oblique or orthogonal magnetic field.

In the differentially rotating gas cloud discussed above, the azimuthal force density given by equation (3) depends on the amount of bend in the field lines. Let us suppose for the moment that most of the bend in the original radial field occurs near the surface of a particular spheroid defined by the quantities \( R, M \). The force equation may then be integrated to give a surface shearing force \( F_\phi \sim B_\phi B_\phi /4\pi \), and the time required to brake the spheroid to the angular velocity of the external system

\[
\tau \sim \frac{G^{1/2}}{B_\phi B_\phi} \left( \frac{M^3}{R^5} \right)^{1/2}.
\]

In the case of the cloud discussed above \( (R = 300 \) pc, \( M = 10^{10} M_\odot \), \( B_\phi = B_\phi = 10^{-4} \) gauss) \( \tau \sim 3 \times 10^9 \) years, which is within the lifetime of a galaxy.

What happens within a particular cloud depends mainly on the distribution of gas density \( \rho \). Thus in a spherical system with \( \rho \) constant, \( M \propto R^3 \) and \( t \propto R^3 \). If a small central cloud is originally rotating rapidly it winds up the field in its vicinity, is braked into co-rotation and then unwinds the fields. A solid rotation system is likely to form near the rotational axis and to spread gradually outwards. At a large distance from the axis \( \rho \) must decrease and it is easily seen that when \( \rho \sim r^{-x} \) where \( x > 4/3 \) the time \( t \) decreases with \( R \) and there is a tendency for gas shells to join the non-rotating intergalactic gas and draw away from the shrinking cloud. The situation is complicated by star formation and disconnection and by the Rayleigh–Taylor instability, but it is likely that a central solid-rotating cloud is isolated and becomes an orthogonal magnetic rotator.

Such a particle accelerator is shown in Fig. 5, comprising a gas cloud \( M = 10^8 M_\odot \), \( R = 3 \times 10^{16} \) cm, angular velocity \( \sim 7 \times 10^{-8} \) s\(^{-1} \), surface speed \( V \sim 2 \times 10^9 \) cm s\(^{-1} \). The cloud has yielded \( 10^{61} \) erg gravitational energy but is far from the Schwarzschild limit \( \sim 3 \times 10^{14} \) cm). The field is poloidal, with some field lines \( (B_i) \) reconnected near the cloud while others \( (B_\phi) \) thread the external
plasma and then connect along the rotational axis to the field of Fig. 4. If the original flux is conserved then the surface field $\sim 10^8$ gauss. The rigidity of this field system ensures co-rotation far beyond the cloud, with an electric field $E = VB \sim 2 \times 10^6$ volts cm$^{-1}$ near the surface of the cloud. Interaction between the non-symmetrical 'magnetosphere' and an external plasma-field system is likely to provide violent electrodynamic disturbances of various types and to accelerate particles by one or other of the mechanisms which have been proposed for pulsars (Piddington 1969a).

![Diagram of a magnetic rotator and proposed source of relativistic particles and of the optical continuum and line emission. Fluctuations in intensity and polarization are caused by rotation of the central magnetized gas cloud.]

Fig. 5. A magnetic rotator and the proposed source of relativistic particles and of the optical continuum and line emission. Fluctuations in intensity and polarization are caused by rotation of the central magnetized gas cloud.

If the rotor is in a vacuum, it will emit electromagnetic waves of frequency $\omega$ and power (Pacini 1967)

$$I = \frac{3}{2} Q^2 \omega^4 c^{-3}$$

(10)

where $Q \sim BR^3$ is the magnetic moment. The above rotator gives $\sim 4 \times 10^{48}$ erg s$^{-1}$ or $10^{61}$ erg in $10^5$ years, much of which is likely to be converted to particle energy (Gunn & Ostriker 1969). On the other hand, if there is an external plasma system the radiation will be largely in the form of shock hydromagnetic waves which also accelerate particles. This mechanism has been suggested for pulsar emission (Piddington 1969b) and after scaling up by a factor $\sim 10^{10}$ may account for the observed optical and radio fluctuations of luminosity and polarization seen in some quasars.

Whether the power output is given by equation (10) or by strong hydromagnetic waves, it may be shown that $I \propto R^{-4}$, so that there is a critical stage of shrinkage.
Before this stage is reached $I$ is too small to be important; afterwards $I$ is adequate to power the sources but the angular momentum is limited and the cloud is braked to a standstill. Such a sequence may explain the observed increase in particle input over a period of perhaps $10^8$ years and its decrease after $10^5$ years. Subsequently the cloud may continue to shrink and may eventually disappear as a singularity.

Some radio sources have more than one pair of components (3C 33.1, 3C 46, 3C 61.1 and others), suggesting the evolution of two or more magnetic rotators within the parent object. It may be that after one gas cloud has disappeared a gaseous shell contracts to replace it and form a second rotator. Alternatively, the first cloud may have developed into a binary system and two magnetic rotators.

Finally, a magnetic rotator may be the source of the primary cosmic radiation in our Galaxy. It has been suggested that in spirals the field and rotational axis are oblique (Piddington 1967a), so that an oblique rotator would be expected. While this might not be powerful enough to provide a strong radio source, it might satisfy the relatively modest requirements of the primary cosmic radiation in our Galaxy.

4.2 The optical objects

The majority of QSOs are radio-free optical sources of extraordinary luminosity (Fig. 1). Nevertheless, their presence in many radio sources (quasars) shows a close relationship and their overall energy requirement of $>10^{60}$ erg suggests a common origin from the gravitational energy of a massive object. The variability in luminosity of some QSOs indicates a size $\gtrsim 10^{16}$ cm and this sets stringent model requirements. The continuum emission is non-thermal and the observation of polarization and also the close relationship with the cm wave polarized sources is strong evidence of synchrotron emission. The other possible non-thermal process is the inverse Compton effect, although some infra-red emission might be provided by the cyclotron process if there are enough electrons of sub-relativistic energies and fields of strength $\sim 10^5$ gauss.

The magnetic rotator of Fig. 5 provides a promising start for a QSO model. The general requirements of the utilization of gravitational energy over a considerable period and at an irregular rate, the disposal of angular momentum, the small size and a powerful magnetic field are all met. By comparison, the stellar collision models (see Burbidge & Burbidge 1967) are deficient in several respects, notably the lack of a field system to remove angular momentum, to accelerate particles and to provide synchrotron emission.

The relativistic electrons are accelerated in the electromagnetic field, where fields $\sim 10^4$ gauss combine with velocities $>10^9$ cm s$^{-1}$ to provide electric fields $>10^5$ volts cm$^{-1}$. Acceleration to energy say $10^{10}$ eV may occur within a distance $10^5$ cm and a time $10^{-5}$ s. Further away from the rotator the electromagnetic field is weaker but more extensive, and acceleration is still effective. Electrons with moderate pitch angles move outward to regions of weaker field and become more closely collimated with the field. Electrons which move transverse to a field $B_\perp$ radiate at a frequency $\nu$ and have a lifetime $\tau$ given by

$$\nu \sim 7 \times 10^{18} B_\perp E^2 \text{ Hz}; \quad \tau \sim 10^{12} \nu^{-1/2} B^{-3/2} \text{ s}. \quad (11)$$

where $E$ is the electron energy in ergs. At the upper limit of the optical range ($3 \times 10^{15}$ Hz, allowing for redshift) and for a field of $10^4$ gauss, $E \sim 2 \times 10^{-4}$ erg
or \( \sim 10^8 \) eV, and \( \tau \sim 0.02 \) s. While this is a very short lifetime, the electrons are generated continuously and in a much shorter period so that it does not present a difficulty. On the other hand, models with much weaker fields require electrons to be accelerated to much higher energies.

Simple models of QSOs and quasars meet the difficulties that inverse compton losses tend to dominate synchrotron losses and that electrons injected from a small central region lose their energy before they travel an appreciable distance (Burbidge & Burbidge 1967). The model of Fig. 5 avoids these difficulties because of the strong magnetic field, because the electrons are accelerated and radiate in situ and because successive layers of plasma radiate at lower frequencies as we move outwards from the central region. Intensity variations are readily accounted for by the rotation of the central object (as in pulsars) and in the model described might have a periodicity equal to the rotation period \( \sim 3 \) years.

The central gas cloud may also explain the optical line emission of QSOs. When the cloud loses enough angular momentum it must contract fast enough to cause substantial heating of the gas and thermal emission. The width of the emission lines (up to 100 ångströms) is accounted for by the rotational speeds \( \sim 10^9 \) cm s\(^{-1}\); the usual explanation of random motions of filaments raises the possibility of disintegration within too short a period. The contracting gas cloud may even account for a shell structure which has been suggested by Shklovskii (1964) and others. Deep within the cloud the gravitational energy per unit mass (\( \propto M/R \)) is much less than that in the surface layers and so the heating may be less. Most of the cloud may comprise cool H\(_I\) with an outer shell of ionized hydrogen.

5. DISCUSSION AND CONCLUSIONS

The electrodynamically-gravitational theory of radio sources requires discussion in relation to various optical objects, to possible tests and to other theories of the sources.

5.1 Discussion

If radio galaxies and quasars are parts of a single evolutionary sequence, then the above theory applies identically. However, the theory does not depend on the identity, but only on the development of sources as twin-synchrotron components moving away from the parent and expanding. In any case, differences in the parent objects may result from different patterns of star formation and decay and different optical efficiencies of the magnetic rotator. The radio-free QSOs have efficient rotators but lack external field systems.

Another aspect of the theory is the relationship between radio galaxies and 'normal' (radio luminosity \( \lesssim 10^{40} \) erg s\(^{-1}\)) galaxies. Since the latter have differential rotation and magnetic fields why do they never match the powerful sources? The answer suggested is that the angle between the rotational axis and the field varies, as one might expect, and that this angle determines not only the radio emission but the form of the parent galaxy (Piddington 1964, 1967a, b). A parallel field would provide no winding or other significant effects while an oblique field would provide weaker winding and a weaker, oblique rotator. This is the explanation of the spiral and irregular sequence of Fig. 2 and of the three sources marked with
squares. M82 is thought to be experiencing the Rayleigh–Taylor instability and the Seyfert galaxies may have oblique rotators. As these decay the galaxies join the spiral and irregular sequence as shown by the dashed line.

There are several possible tests of the model, the most obvious being a search for extended coronas ($\gtrsim 100$ kpc) of field and plasma lying along and twisted around the rotational axis of ordinary elliptical galaxies. Just such a test is also required for the recent explanation of QSO absorption lines in terms of extended galactic coronas (Bahcall & Spitzer 1969). Another observational test is for magnetic rotators in QSOs and Seyfert galaxies and even in some spiral systems. Rotation might be detected by a pattern of line emission or by a periodicity in luminosity, as in pulsars but with periods of some years. Finally, since a spent gas cloud may collapse into a singularity, these objects should be sought by their gravitational effects in galactic central regions.

5.2 Conclusions

(a) The mechanism of electrodynamic conversion of gravitational energy (Piddington 1964, 1966) allows continuous conversion over a long period and obviates the disturbing conclusion that the behaviour of sources cannot be explained in terms of conventional physical theory (Hoyle 1969). It removes angular momentum and so explains why elliptical galaxies with much angular momentum per unit mass frequently become radio galaxies.

(b) Perhaps the most stringent requirement of a source model is the magnetic field, which is present before the source and has very great energy ($\gtrsim 10^{90}$ erg), flux and extent, as well as a systematic orientation.

(c) The earlier theory of continuous magnetic amplification until loss of equilibrium is now modified by the intervention of the Rayleigh–Taylor instability and hence the formation of a twisted, external field system (Fig. 4) during the evolution of the optical galaxy ($\sim 10^{10}$ years). Eruptions in M 82 and NGC 1275 may reveal this effect.

(d) A star-depleted gas cloud of mass $\sim 10^8 M_\odot$, radius $\sim 10^{16}$ cm, surface speed $\sim 10^6$ cm s$^{-1}$ with a frozen-in field $\sim 10^6$ gauss forms a magnetic rotator (Fig. 5). It provides the relativistic particles for the radio sources and the QSOs by one or other of the proposed pulsar mechanisms. Rotation provides recurrent bursts of particles and accounts for variations in luminosity and polarization. Previous model difficulties are now met by the strong field and by the acceleration and synchrotron emission in situ.

(e) The fast-shrinking gas cloud heats up to provide the QSO line emission. Broad emission lines are provided by the fast rotation, and shell structure by uneven heating.

(f) Finally the cloud shrinks into a singularity and disappears. In some cases its place may be taken by a second gas cloud of shell form which is magnetically braked and so follows the same sequence and provides another radio source and QSO.

(g) The theory is very simply extended to 'normal' galaxies to explain different forms, central regions of high mass density and low angular momentum density, central activity and spiral forms. In particular an oblique magnetic rotator (Fig. 5) may explain the radio emission of some spirals and the origin of most cosmic rays, including those in our Galaxy.
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REFERENCES


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