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Abstract

Activity in galaxies and quasars is interpreted in terms of plasma processes occurring in the magnetosphere of a certain magnetoid model. This magnetoid comprises a core and an annulus rotating about a common axis with different angular velocities. The magnetic field linking the core to the annulus may begin in an initial current-free state but will be distorted along a sequence of force-free configurations. After a finite differential rotation, the force-free configuration has higher energy than a corresponding open-field configuration. It is conjectured that the transition from the closed configuration to an open configuration will be effected by an MHD "eruptive" instability, and that such eruptions lead to high-velocity clouds of cool gas identified with clouds producing absorption lines in quasars. The open magnetic-field configuration necessarily contains current sheets. The magnetic free energy of these current sheets may be released explosively by the flare mechanism. The ejection of radio clouds from galaxies and quasars is attributed to "galactic flares". Current sheets contain mildly relativistic electrons moving in directions partially transverse to the magnetic field. Synchrotron radiation from these electrons is held to be responsible for the non-thermal radiation from quasars and certain galaxies. It is proposed that minor instabilities of the current sheets are responsible for fluctuations in the non-thermal luminosity and for small-scale radio bursts sometimes observed in galaxies and quasars.

ACTIVITY IN GALAXIES AND QUASARS

1. Introduction

The basic problem concerning radio galaxies, and one of the principal problems concerning quasars, is that of understanding the mechanism of the explosion which typically produces a pair of radio clouds moving from the object in opposite directions (Ryle, 1968). In previous articles (Sturrock, 1965, 1966b, 1969), I have drawn attention to the apparent similarity between these explosions and solar flares (Sturrock, 1966a, 1968) and proposed that the explosion mechanism is the same in both phenomena. This has led to the view that the explosion (termed a "galactic flare") originates in a current sheet (or "sheet pinch") and that the energy released in the explosion is the magnetic free energy associated with this current.

This model appears to account satisfactorily for the directional ejection of "plasmoids", each of which comprises high-energy particles and comparatively cool gas, locked together in a magnetic field. The configuration which such a plasmoid would adopt has been calculated by Mills and Sturrock (1970), following the suggestion advanced by De Young and Axford (1967) that confinement is effected by the ram pressure of the intergalactic medium. The results agree well with observation (Wardle and Miley, 1971) and support the view that an explosion is a galactic flare.

Although the presence of a large amount of cool gas in the plasmoids ejected by a galactic flare was not foreseen in the earlier articles, it is consistent with the known properties of plasmoids ejected by solar flares (Hundhausen, Bame and Montgomery, 1970). The way in which this occurs will be discussed briefly in Section 3.

In earlier articles (Sturrock, 1965, 1966b, 1969) it was proposed that the current sheets develop during the gravitational contraction of a mass of intergalactic gas to form a quasar or radio galaxy. However, in order to explain the double-ejection process, it was necessary to assume that each quasar or galaxy which exhibits such an explosion condenses from intergalactic matter in the vicinity of a primeval current sheet and that the magnetic-field configuration is not significantly affected by rotation of the object. These are implausible assumptions which it is better to avoid.

Another important problem concerning quasars is their high non-thermal luminosity. In this respect, quasars resemble the nuclei of Seyfert galaxies. The luminosity of the quasar 3C 273 is estimated at $10^{47.5}$ erg sec^{-1} (Low and Kleinmann, 1969). Compared with stellar (thermal) spectra, the spectra of quasars and of the nuclei of Seyfert galaxies show both a blue excess and a red excess. It appears, from infrared observations, that the spectra may typically peak in the infrared part of the spectrum (Low and Kleinmann, 1969). The radiation exhibits time variations on time-scales ranging from years down to days, and there is evidence of both linear and circular polarization (Schmidt, 1969; Nikulin, Kuvshinov and Severny, 1971).

The discovery of pulsars, and the development of theories of pulsars, have led to the view that quasars and active galaxies may derive their energy from rotation (Morrison, 1969; Fowler, 1971; Woltjer, 1971). In such an object, loss of rotational energy involves loss of angular momentum, which then leads to contraction. In this way rotational energy is continually replenished (and, indeed, augmented) by gravitational energy, but there are difficulties in interpreting the high nonthermal luminosity of quasars as a manifestation of the conversion of rotational energy by a pulsar mechanism (Sturrock, 1971).

In the models recently proposed by Ozernoi and Somov (1971) and by Piddington (1970), the energy released in explosions is attributed to differential rotation. Piddington attributes explosions to a magneto-hydrodynamic instability which can explain the ejections but not the particle acceleration. Ozernoi and Somov attribute explosions to field-line reconnection (i.e., to flare action) but their magnetic-field geometry is not such that one flare will clearly lead to double ejection, as is typical of explosions in quasars and radio galaxies.

It seems that a satisfactory account of galactic explosions would be provided by the galactic-flare model, provided that there is a mechanism for converting the energy of differential rotation into the magnetic free energy associated with current sheets and provided that the magnetic-field configuration is such as to lead to double ejection. This article presents a model which involves such a mechanism, and for which the magnetic-field topology is such as to lead to double ejection. Furthermore, this model includes a mechanism for the production of high non-thermal luminosity with some of the properties associated with the continuum luminosity of quasars and Seyfert galaxies.

In Section 2, a simple model of a massive differentially-rotating object will be proposed. The evolution of a magnetic field associated with this object (comprising a "magnetoid") will be discussed, based on a recent analysis by Barnes and Sturrock (1971). It will be seen that differential rotation can lead to the generation of a current-sheet system similar to that hypothesized previously. The properties of galactic flares to be expected on this basis will be discussed in Section 3. Properties of the current sheet will be discussed in Section 4, where it will be argued that synchrotron radiation from the current-carrying electrons can provide the nonthermal luminosity of quasars and active galaxies. Further thoughts and questions raised by this theory will be discussed in Section 5.

2. Magnetic-Field Evolution in a Differentially Rotating Object

We are concerned with the evolution of a magnetic field associated with a self-gravitating massive differentially-rotating object. We expect that, within a certain region, the magnetic stresses will be substantially less than the gravitational and inertial stresses. Outside a larger region, we expect that the gas density will be sufficiently small that the magnetic energy density exceeds the thermal energy density. However, if there is any degree of ionization, it will be possible to consider the gas to be highly conducting on account of the large spatial dimensions involved (Cowling, 1957). The same conditions are known to arise in the solar atmosphere as now appear to arise in the magnetoid magnetosphere. Following knowledge developed from study of solar problems (Barnes and Sturrock, 1971), we may conclude that the magnetic-field pattern in the atmosphere of the massive object comprises two types of magnetic-field configurations: (a) force-free configurations; and (b) current sheets. The aim of the present section is to determine what combination of these two configurations will arise in a differentially rotating magnetoid.

We consider, as a simple model of a differentially rotating magnetoid, the configuration shown in Figure 1(a). The magnetoid here comprises a disk-shaped central region of radius R and an annular sheet, the outer radius of which may be several times R. We suppose that the mass of the central region is M_C (gm) and that of the annular region M_A. We introduce cylindrical co-ordinates z, r, ϕ, and suppose that there is a cylindrically symmetric magnetic field, of total flux Φ (gauss cm^2), linking the core to the annulus. In the absence of differential rotation, $B_\phi = 0$ and the magnetic field adopts the current-free configuration shown schematically in Figure 1(a). The key question is to determine how this magnetic pattern changes when the annulus and core suffer a relative angular displacement ψ.

A specific example of the above configuration has been computed, by relaxation methods, by Barnes and Sturrock (1971). Rather than present the specific calculation in detail, the salient results will be shown schematically. It is clearly necessary that a toroidal component B_ϕ should develop. This gives rise to a tension in the ϕ direction which produces a torque resisting differential rotation. It also gives rise to an increased magnetic pressure in the meridional plane, which has the effect of "inflating" the magnetic-field pattern. This may be seen by comparing Figure 1(a) and Figure 1(b), which indicates the degree of inflation which occurs when $\psi = \pi$.

The most important parameter of the force-free magnetic-field configuration is the energy W (erg). This may be written as

$$W = F(\psi)\, \Phi^2 R^{-1} . \qquad (1)$$

The dimensionless function $F(\psi)$ is shown in Figure 2 over the range $0 \leq \psi \leq 3\pi$, for which calculations have been made. It is seen that, after an initial parabolic region, the function F becomes almost linear in ψ: $F(\psi) \sim 0.2\,\psi$. The torque Θ (dyne cm) resisting differential rotation is given by

$$\Theta = F'(\psi)\, \Phi^2 R^{-1} . \tag{2}$$

The coefficient $dF/d\psi$, which is given in Figure 2, initially increases linearly, then tends asymptotically to the approximate value 0.2.

The key question to be posed is whether differential rotation will lead to the formation of current sheets. The most extensive current sheet which could be formed is shown in Figure 1(c): all the magnetic field lines from the core and annulus are open, extending to infinity. In the Barnes-Sturrock model, the magnetic energy of this configuration is given by equation (1), with the value $F_S = .745$. We now see, from Figure 2, that the energy of the force-free magnetic-field configuration exceeds that of the completely open configuration if $\psi > \pi$ (approximately). The significance of this result is that, <u>if $\psi > \pi$, the force-free magnetic-field configuration is either unstable or metastable</u>, since the open-field configuration represents an accessible lower-energy state.

It will be important to decide exactly where the onset of instability occurs, and whether the onset of instability is explosive or nonexplosive (Sturrock, 1966c). If the onset is nonexplosive, field lines will open gently (there will be an "exchange of stability"), so that no significant amount of energy is dissipated in the process of opening field lines.

The fact that the numerical calculation of force-free fields can be carried out in a stable manner for $\psi > \pi$ indicates that each force-free field configuration has some measure of stability. This indicates that each such pattern is metastable: an appropriate finite-amplitude perturbation would then trigger an explosive instability, leading to the formation of open field lines. The conversion might occur completely in one step or, more likely, would occur progressively in smaller steps, an intermediate configuration being of the form shown in Figure 1(d).

It appears, therefore, that the differential rotation converts a stable current-free magnetic-field configuration into a force-free configuration which is metastable. Such a configuration is subject, upon perturbation, to an explosive instability which we term an "eruption" or "eruptive instability". This will be magnetohydrodynamic in character, not involving the violation of the "frozen-flux" condition. It would therefore not lead to significant particle acceleration. On the other hand it would lead to the expulsion of magnetic field, which must be accompanied by the expulsion of a certain amount of plasma in that region of the magnetosphere. The expulsion would take place at a speed comparable with the Alfven speed where the eruption occurs. It is believed that the eruptive instability which occurs in the present context occurs also in solar active regions and is there responsible for erupting prominences (Kiepenheuer, 1953). The solar phenomenon is explosive, but is a magnetohydrodynamic phenomenon which does not involve particle acceleration.

We see that, when differential rotation commences, the magnetic energy begins to increase. After rotation has proceeded by some fraction of a complete rotation, the magnetic-field configuration will be metastable and will lose energy by conversion into a configuration which is partly or completely open. Such a conversion is expected to be explosive. Before one complete rotation has been made, we expect that the magnetic-field configuration will be converted into one which is substantially completely open. As we see from Figure 2, the energy of the open-field configuration exceeds that of the initial current-free configuration by almost 90%.

3. Galactic Flares

It is known that a current sheet is metastable, being subject to an instability which leads to field-line reconnection and returns the magnetic field to the current-free state. This instability is responsible for energy release in solar flares so that such instabilities, which are explosive, will in the present context lead to "galactic flares". The magnetic free energy associated with the current sheet is converted into kinetic energy, of which part may be the kinetic energy of mass motion, and part may be the kinetic energy of high-energy particles. The linear theory of this instability has been discussed by Furth, Killeen and Rosenbluth (1963), Laval, Pellat, and Vuillemin (1966), and others, and the nonlinear stage by Petschek (1964) and others. It now begins to appear that plasma turbulence plays an important part in the reconnection process, as has been discussed by Sturrock (1968), Friedman and Hamburger (1969), and Coppi and Friedland (1971). In this section, I shall discuss only the gross consequences of the reconnection process in its relation to the present model.

First it is advisable to make a slight generalization of the magnetoid model discussed in Section 2. Rather than assume that the magnetic flux threading the core and the annulus are equal, we consider the possibility that the core is small, both in mass and in magnetic flux, compared with the surrounding annulus. The magnetic-field pattern will then resemble more closely that shown in Figure 3 when it is in the force-free state, and that shown in Figure 4 after a current-sheet has developed. We now suppose that reconnection begins to occur in the current sheet, which is topologically cylindrical in form. Our knowledge of solar flares (Sturrock, 1968) suggests that the instability will begin at low "heights" in the neighborhood of a magnetoid, and will then progress to greater heights. The behavior of solar flares also indicates that, if reconnection begins at one point of the "neck" of the cylinder, it will rapidly lead to tearing all the way round the neck. An early stage of the reconnection process will therefore be as shown in Figure 5.

The reconnection gives rise to particle acceleration, so that high-energy electrons and protons will stream in two directions: out into the open-field region, and in toward the surface of the magnetoid. The outward-streaming electrons will subsequently be responsible for radio emission of the ejected radio clouds. The inward-streaming particles heat the outer region of the magnetoid. One result is likely to be the production of radiation extending from optical line emission to non-thermal hard x-ray emission, as is the case in solar flares. The other result, again drawn from our knowledge of solar flares, is that heating of the outer layers of the magnetoid will lead to evaporation of gas into the reconnection region. Since heat can be propagated across magnetic field lines in the deep atmosphere of the magnetoid, this evaporation will proceed slightly in advance of field-line reconnection. The end result, as indicated in Figure 6, is that, after reconnection has ceased, a large mass of hot gas will be contained in the new closed-field region, and a comparable mass of gas will be contained in the reconnected open field lines. Based on our knowledge of solar flares, we would expect the hot plasma in the closed-field region to produce long-lived quasi-thermal x-ray emission. The inward heat flux from this region may also lead to long-lived enhanced line emission from the atmosphere of the magnetoid.

The most interesting behavior, following field-line reconnection, now occurs in the two annular plasmoids, produced in the open-field region. Each plasmoid contains high-energy electrons and protons and a large mass of gas which is initially hot but which will cool by radiation. The tension of the open magnetic field lines and the stresses of the closed field lines both lead to the ejection of these plasmoids. It will be noted that the flare has thereby led to the ejection of two plasmoids in opposite directions along the axis of rotation of the magnetoid. This model therefore explains one of the important characteristics of explosions in radio galaxies and quasars.

The speed of ejection of the two plasmoids will be determined by the magnetic stresses and the inertia of each plasmoid. The order of magnitude of the ejection speed will therefore be the Alfven speed in the part of the magnetoid containing the hot dense gas. However, as each plasmoid moves away from the magnetoid in the axial direction, it moves into a region of decreasing magnetic field strength, so that expansion will lead to a reduction also of the internal magnetic field strength. This leads to a progressive decrease of the local Alfven speed. In consequence, after each plasmoid has travelled a distance comparable with the size of the magnetoid, it will be moving at a super-Alfvenic speed. When this occurs, the magnetic-field lines will begin to trail behind each plasmoid. It is difficult to see just how the magnetic field lines will rearrange themselves, and it is possible that they will become quite tangled in the process. However, the end result will be similar to the configuration shown in Figure 7. For simplicity, the diagram shows only the strong-field region, near the magnetoid and each plasmoid, not the complete field pattern. Each plasmoid then resembles the model discussed by Mills and Sturrock (1970), and is subject to confinement by the ram-pressure of the intergalactic medium. It may be noted that there is necessarily a current sheet in the "tail" of each plasmoid, so that further flare activity could possibly occur in this tail. This may conceivably be the explanation of the jet of the quasar 3C 273, which extends from the radio cloud 3C 273A some distance toward the quasar situated at 3C 273B.

Although a galactic flare returns the magnetic field, coupling the core to the annulus of a magnetoid, to its current-free state, further differential rotation will lead to the same evolution as was discussed in Section 2, so that a further eruptive instability, or sequence of such instabilities, will lead to the generation of a new current-sheet configuration. This configuration will again be subject to the flare instability, leading to the repeated ejection of plasmoids in the two directions parallel to the rotation axis. This model therefore accounts satisfactorily for the repeated ejection of pairs of radio clouds in fixed directions. Observations favor the view that this direction is the rotation axis of the object (Moffet, 1966).

We conclude this section by discussing briefly the numerical values of parameters which arise in the theory. We first consider the total energy released by a galactic flare. Maltby, Matthews and Moffet (1963) have estimated the parameters of radio clouds of a number of identified radio sources, typically radio galaxies. From their estimates of the magnetic field strength and volume of each radio cloud, it is possible to estimate the magnetic flux of each cloud, which is typically $10^{41.5}$ gauss cm^2. The total energy in either relativistic electrons or magnetic field is typically 10^{59} erg. However, studies of the ram confinement model (Mills, 1971) have shown that the kinetic energy of mass motion of a radio cloud is typically 100 times the energy in relativistic electrons. The total energy involved in the radio clouds considered by Maltby, Matthews and Moffet is therefore probably of order 10^{61} erg.

The model discussed in Section 2 indicates that the energy released in a flare may be as large as

$$W_{FE} = 10^{-0.5} \Phi^2 R^{-1} . \qquad (3.1)$$

If we adopt the estimate $\Phi = 10^{41.5}$ gauss cm^2 and $W_{FE} = 10^{61.3}$ erg (since there are typically two clouds per explosion), equation (3.1) leads to the estimate $R = 10^{21.2}$ cm or 500 pc. This is not an unreasonable value for the scale of a nucleus of a radio galaxy: for instance, Cygnus A shows a nucleus with double structure, the scale of the structure being 1 kpc.

It has been shown elsewhere (Sturrock, 1967) that the virial theorem requires that

$$\Phi = \alpha \,.10^{-3} M_C \,, \quad \alpha \leq 1 \,, \tag{3.2}$$

where M_C (gm) is the mass of the "core" of the magnetoid. The preceding estimate of Φ then leads to the condition $M_C > 10^{11.2} M_\odot$. This is large but perhaps not unacceptable, since radio galaxies typically have massive nuclei.

The above numbers should, in any case, be treated with caution. Estimates of magnetic flux and energy of radio clouds are subject to substantial error. The above considerations merely establish that these estimates are not incompatible with possible values of the mass and radius of the nucleus of a radio galaxy.

In addition to considering the gross features and gross parameters of galactic flares, it is desirable to examine a particular case in more detail. It is argued elsewhere that the jet of M87 is the observational manifestation of a galactic flare, and parameters for this case have been calculated (Sturrock, 1969).

4. Continuum Luminosity

It has been noted that, in addition to displaying explosive behavior, quasars are notable also for their high nonthermal luminosities, and that some galaxies (such as Seyfert galaxies) also show strong nonthermal contributions to their optical and infrared luminosities.

The present model suggests an explanation of this phenomenon. If the magnetoid develops a current sheet, the current will be carried by charged particles (predominantly by electrons) which must have velocity components transverse to the direction of the local magnetic field. These electrons will therefore radiate by the synchrotron mechanism. It is interesting to make a simple estimate of the magnitude of this radiation.

If the thickness is taken to be b (cm), we see from

$$\nabla \times \underset{\sim}{B} = 4\pi \underset{\sim}{j} , \tag{4.1}$$

that the current density j (e.m.u.) is given by

$$j \approx 10^{-0.8} \, B \, b^{-1} , \tag{4.2}$$

since the field strength changes by 2B across the sheet. The current density j is related to the electron density n (cm^{-3}) by

$$j = \frac{ne}{c} v \approx ne = 10^{-9.3} \, n , \tag{4.3}$$

assuming that the electrons are relativistic. The total number N of electrons in the "strong-field" region of the current sheets is approximately

$$N = 4\pi R^2 bn , \tag{4.4}$$

which, from (4.2) and (4.3), becomes

$$N = 10^{9.6} \, B \, R^2 . \tag{4.5}$$

Since electrons are radiating, they are continually losing energy.

If the electrons are highly relativistic, this loss of energy will not involve a loss of current, and there will be no change of magnetic field to induce an accelerating electric field. However, if the electrons are nonrelativistic, loss of energy will lead to a sharp decrease in current, which will then lead, via a change in the magnetic field, to an induced accelerating electric field. These considerations suggest that the majority of electrons in the current sheet will be mildly relativistic.

We suppose that the continuum radiation is produced by the synchrotron mechanism, and we assume the radiation to be self-absorbed at low frequencies. We assume that the luminosity spectrum L_ν has the peak value $L_{\nu,M}$ at the frequency ν_M. Then the total luminosity L is related to these quantities by the approximate relation

$$L \approx \nu_M L_{\nu,M} . \tag{4.6}$$

If the electrons responsible for radiation at ν_M have energy E_e, then (Shklovsky, 1960)

$$\nu_M = 10^{-5.3} E_e^2 B , \tag{4.7}$$

and the power (erg sec^{-1}) emitted per electron is

$$S_1 = 10^{-26.1} E_e^2 B^2 , \tag{4.8}$$

so that

$$L = N S_1 = 10^{-16.5} E_e^2 B^3 R^2 . \tag{4.9}$$

Formulas for synchrotron self-absorption (Le Roux, 1961; Dent and

Haddock, 1966) show that

$$L_{\nu,M} = 10^{-29.0} R^2 B^{-\frac{1}{2}} \nu_M^{5/2} . \tag{4.10}$$

On the other hand, equations (4.6), (4.7), and (4.9) show that

$$L_{\nu,M} = 10^{-11.5} B^2 R^2 . \tag{4.11}$$

Comparison of equations (4.10) and (4.11) shows that

$$\nu_M = 10^{7.0} B . \tag{4.12}$$

Comparison of equations (4.7) and (4.12) shows that electrons responsible for radiation at the peak of the spectrum have energy $E_e = 10^{6.2}$ eV. Hence equation (4.9) becomes

$$L = 10^{-4.1} B^3 R^2 . \tag{4.13}$$

It is interesting to note that these considerations lead to the same conclusion as was previously obtained by a quite different argument, that the majority of radiating electrons are mildly relativistic.

It is convenient to represent the radius R by

$$R = \rho R_S , \qquad \rho > 1 , \tag{4.14}$$

where R_S is the Schwarzschild radius, given by

$$R_S = 2 G M_C c^{-2} = 10^{-27.9} M_C . \tag{4.15}$$

With the approximation

$$\Phi \approx \pi R^2 B , \tag{4.16}$$

we find from equation (3.2) that

$$B = 10^{52.5} \alpha \rho^{-2} M_C^{-1} , \qquad (4.17)$$

so that equations (4.12) and (4.13) become

$$\nu_M = 10^{59.5} \alpha \rho^{-2} M_C^{-1} , \qquad (4.18)$$

and

$$L = 10^{97.6} \alpha^3 \rho^{-4} M_C^{-1} . \qquad (4.19)$$

Let us now consider the quasar 3C 273. The infrared spectrum is not known in detail but it appears (Low and Kleinmann, 1969) that the total luminosity $L \approx 10^{47.5}$ erg sec^{-1} and that the spectrum peaks at about $\nu_M = 10^{12.5}$ sec^{-1} (assuming that the distance can be inferred from the redshift by the Hubble relation). If we substitute these values into (4.18) and (4.19), we find that

$$\alpha \rho^{-2} M_C^{-1} = 10^{-47.0} , \qquad (4.20)$$

and

$$\alpha^3 \rho^{-2} M_C^{-1} = 10^{-50.1} . \qquad (4.21)$$

On noting that $\alpha < 1$ and $\rho > 1$, we find that M_C is in the range

$$10^{10.5} M_\odot < M_C < 10^{12.1} M_\odot . \qquad (4.22)$$

The values corresponding to the center of this range are as follows:

$$\left.\begin{aligned} &\alpha = 10^{-0.8}, \quad \rho = 10^{0.8}, \quad M_C = 10^{44.6} g = 10^{11.3} M_{\odot} \\ &R = 10^{17.5} \text{ cm}, \quad B = 10^{5.5} \text{ gauss}, \quad \Phi = 10^{41.0} \text{ gauss cm}^2 \\ &W_{FE} = 10^{64.0} \text{ erg} \quad . \end{aligned}\right\} \quad (4.23)$$

We find from the virial theorem [equation (2.5), Sturrock, 1971] that the rotation period of this object would be of order 10 years. Hence this model would be consistent with the reality of the conjectured 13-year periodicity (Smith and Hofleit, 1963) of 3C 273.

It will be noted that the radius of this object is only a few times the radius of the black hole with the same mass. This suggests that a substantial fraction of the mass of this object would be in the form of a black hole, the remainder of the mass perhaps being in the process of capture by the black hole, a proposal which has previously been advanced by Lynden-Bell (1969).

The radius of the continuum region of the preceding model of 3C 273 is four light months. This is perhaps consistent with the fact that this object is known to show light fluctuations with the time scale of months. However, variations sometimes occur on a shorter time scale. In attempting to reconcile this fact with the present model, we should bear in mind that the radiation is being produced by streams of mildly relativistic electrons. The radiation will therefore be beamed in the direction in which electrons are streaming. It is therefore probable that the light received by a particular observer will typically be derived from only a small region of the current sheet. Fluctuations of this small region may give rise to light variations with a time scale much shorter than the time it takes light to travel one complete diameter of the object.

Finally, we may note that synchrotron radiation from mildly relativistic electrons should produce not only linear polarization, which appears to be an intrinsic property of most quasars (Schmidt, 1969), but also circular polarization, which has possibly been detected in the Seyfert galaxies NGC 1068 and NGC 4151 and in the quasar 3C 273 by Nikulin, Kuvshinov and Severny (1971).

5. Discussion

We see from the preceding section that an object which exhibits activity on a galactic scale (quasar, radio galaxy, Seyfert galaxy, etc.) will pass through three distinct stages. Stage 1 may be termed the "ground state" in which the magnetic field linking the core to the annulus is current-free. Stage 2 comprises a force-free (but not current-free) magnetic field linking the core to the annulus. Stage 3 is the configuration in which magnetic field lines which might couple the core to the annulus adopt an open configuration, creating a current sheet. The transition from stage 1 to stage 2 is the result of differential rotation. The transition from stage 2 to stage 3 is effected by an eruptive instability. The transition from stage 3 back to stage 1 is caused by a galactic flare.

It is proposed that objects with high nonthermal luminosities (quasars, Seyfert galaxies, and some N-type galaxies) are in stage 3 of this sequence. Radio galaxies have recently experienced a galactic flare, which may have returned them to the "ground state" of stage 1. However, it is possible that a minor flare may occur which will produce one or more radio clouds but may leave the current sheet substantially intact. It is well known that solar flares occur with a wide range of energy, and that low-energy flares occur more frequently than high-energy flares, and the same may well be true of galactic flares. It appears likely that small-scale flares are responsible for the radio bursts studied by Kellerman and Pauliny-Toth (1968) and others.

We have discussed the observational manifestation of galactic flares, which we associate with the transition from stage 3 to stage 1. The eruptive instability, which marks the transition from stage 2 to stage 3, may also have observational consequences. Since this instability is magnetohydrodynamic in character, it will not involve particle acceleration, but it will lead to the expulsion of a plasmoid comprising gas and magnetic field. Since the large mass of gas ejected by a galactic flare is evaporated during the flare process, and since there is no comparable process during an eruptive instability, it seems likely that the mass of gas ejected by an eruptive instability will be much less than that ejected by a galactic flare. As with galactic flares, the plasmoid will be ejected with the local Alfven speed. After some time, the object will be moving at super-Alfvenic speeds so that the configuration will be similar to that of Figure 7, field lines trailing behind the "head" of the plasmoid, which contains the mass of gas, and a shock wave forming in front of the plasmoid. The plasmoid will therefore be subject to ram confinement. In addition, we note that the stabilizing action of a shock wave will tend to make the entire object move with a well defined velocity.

These considerations suggest that absorption-line features in quasars [and in the Seyfert galaxy NCG 4151 (Anderson and Kraft, 1969)] may be due to an eruptive instability. The gas is not subject to heating by flare action, and it will tend to cool by radiation. If the line of sight to the quasar or Seyfert nucleus intersects such a plasmoid, absorption lines will be produced. Shock stabilization of a ram-confined plasmoid offers an explanation of the small velocity dispersion of ejecta responsible for absorption lines. Since these plasmoids will be decelerated by ram pressure, plasmoids of highest speed will be close to the parent object, and those with lowest speeds will be furthest away.

The analogy between galactic activity and solar activity also suggests an explanation of emission-line regions in quasars and Seyfert galaxies. The development of force-free fields, of current sheets, and of reconnection of these sheets may lead to magnetic-field configurations similar to those which support quiescent prominences in the sun's corona (Tandberg-Hanssen, 1967). These magnetic-field configurations have the important property that they can support a certain amount of gas in a stable manner against the force of gravity. When this situation arises, low-temperature gas collects in these "magnetic troughs" by a thermal instability or condensation process (Pikel'ner, 1971). Irradiation of this gas by ultraviolet light from the current sheet leads to excitation and emission-line radiation.

Although a simple model of a magnetoid has been adopted for convenience in calculation and discussion, it must be stressed that this model was introduced simply for illustration. A real quasar or galactic nucleus may consist of several components or of a continuous distribution of mass with differential rotation. The fact that quasars do not display striking periodicity points towards a more complex model of this type. Similarly, there is no reason to expect that the magnetic field exhibits strict cylindrical symmetry. It may be more complex: for instance, the magnetic field of the core may be dipolar in form, but the dipole axis may be inclined at an angle to the rotation axis. The force-free magnetic field produced by differential rotation in such an object would be much more difficult to calculate. Nevertheless, it appears that the magnetic field configuration would go through the same three stages as were introduced earlier in this section, and that transitions would take place by the same mechanisms.

These considerations suggest that radio clouds will be produced in more complex magnetoids, but the structure of the resulting clouds will be correspondingly more complex than the models suggested here and elsewhere (Mills and Sturrock, 1970). Furthermore, we should also note the possibility that a flare occurs in a magnetic-field configuration which is only partially open, as shown in Fig. 1(d). Then a flare may occur in one "hemisphere" of the magnetoid magnetosphere and fail to trigger a flare in the other hemisphere. In this case, only one plasmoid would be ejected, and only one radio cloud would be observed.

As a summary of the ideas outlined in this article, Figure 8 gives a "flow diagram" showing the various mechanisms of energy conversion which arise in this model for activity in galaxies and quasars.

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FIGURE CAPTIONS

Figure 1. Magnetic-field configurations of a model magnetoid with differential rotation: (a) current-free field pattern; (b) force-free field pattern developed after differential rotation through angle π; (c) open field pattern; (d) partially open pattern.

Figure 2. Variation of parameter F characterizing magnetic-field energy as a function of ψ, angle of differential rotation.

Figure 3. Current-free magnetic-field configuration of magnetoid for case that flux threading core is smaller than flux threading annulus.

Figure 4. Open magnetic-field configuration developed in model shown in Figure 3.

Figure 5. Early stage of galactic flare occurring in magnetoid shown in Figure 4.

Figure 6. Late stage of galactic flare occurring in magnetoid shown in Figure 4.

Figure 7. Galactic flare gives rise to ejection of two plasmoids and returns magnetic field to current-free state.

Figure 8. Flow diagram for energy conversion in quasars and active galaxies.

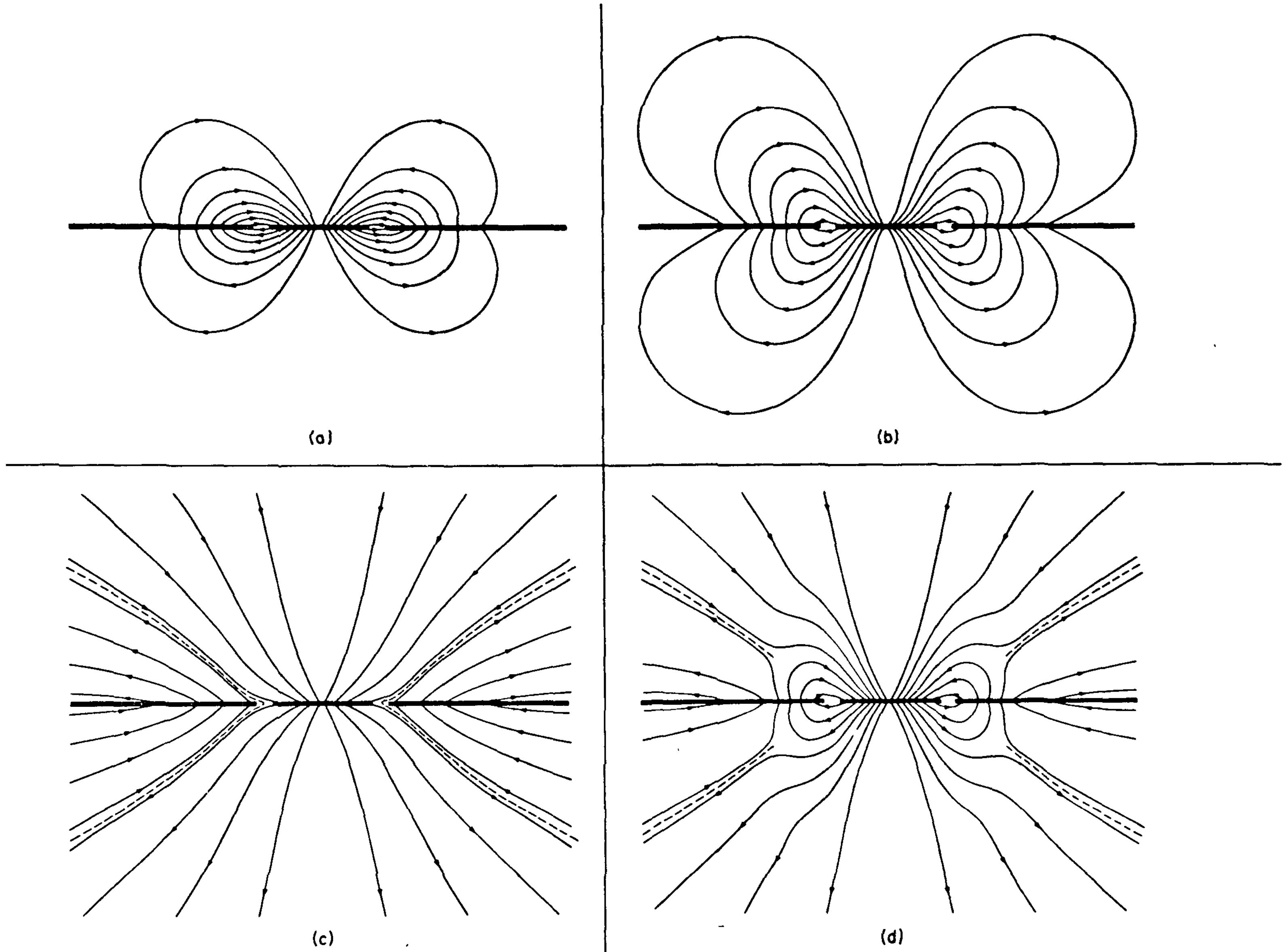

Figure 1. Magnetic-field configurations of a model magnetoid with differential rotation: (a) current-free field pattern; (b) force-free field pattern developed after differential rotation through angle π; (c) open field pattern; (d) partially open pattern.

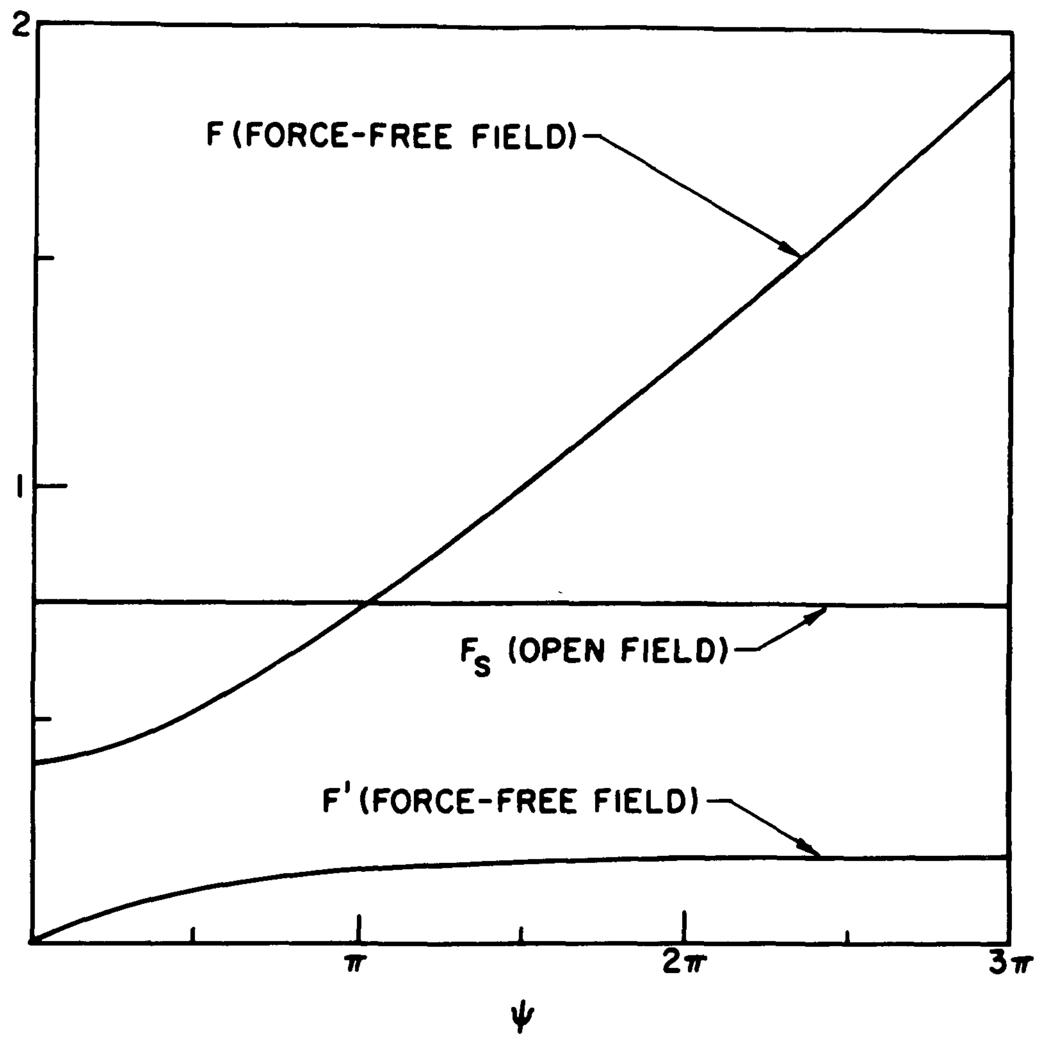

Figure 2

Variation of parameter F characterizing magnetic-field energy as a function of ψ, angle of differential rotation.

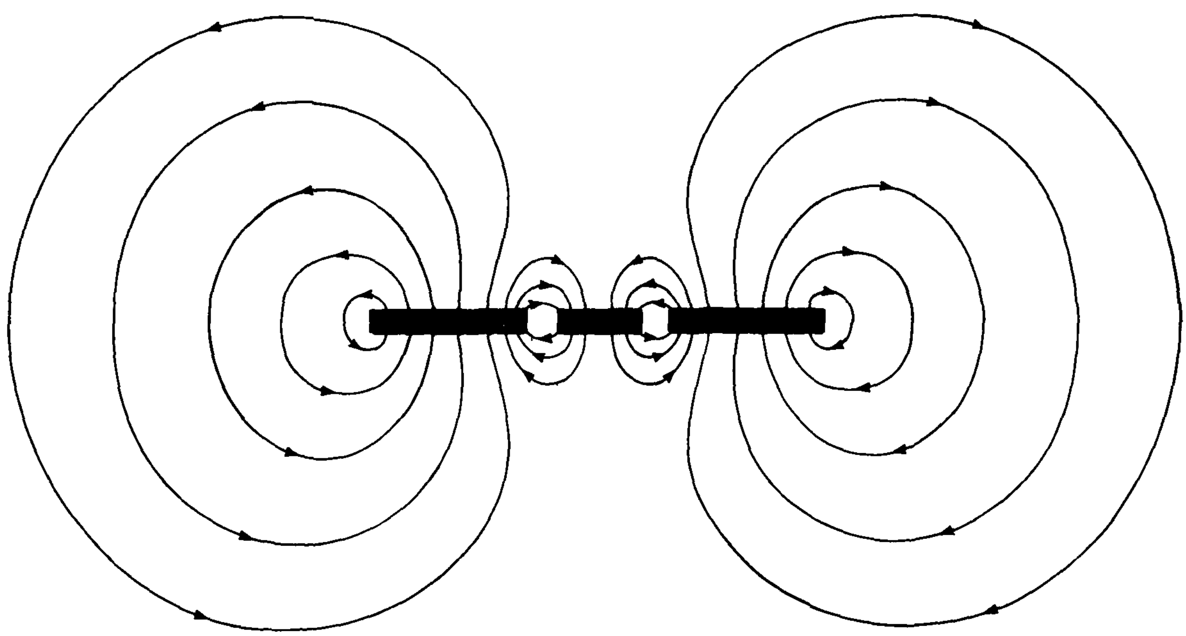

Figure 3

Current-free magnetic-field configuration of magnetoid for case that flux threading core is smaller than flux threading annulus.

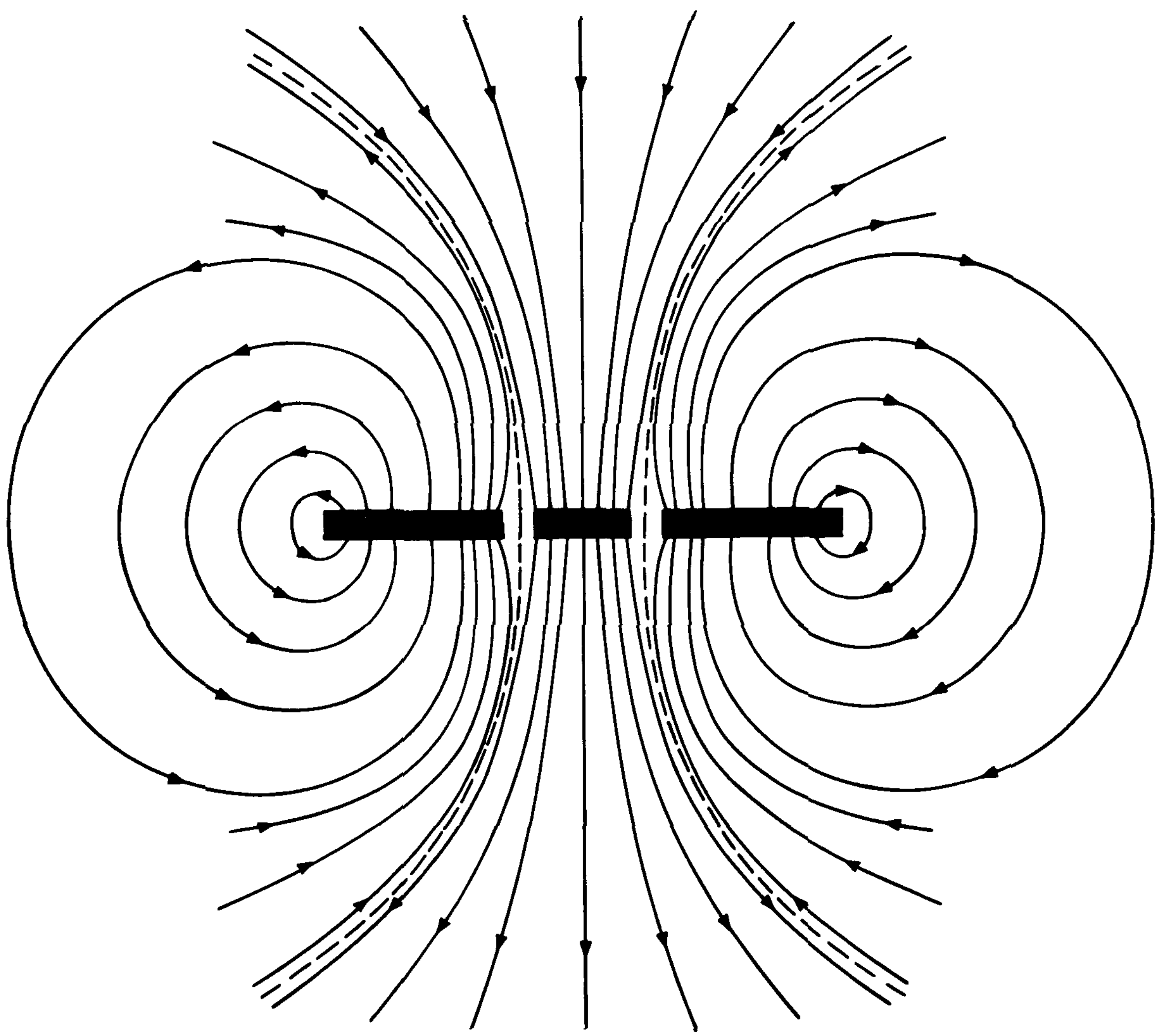

Figure 4

Open magnetic-field configuration developed in model shown in Figure 3.

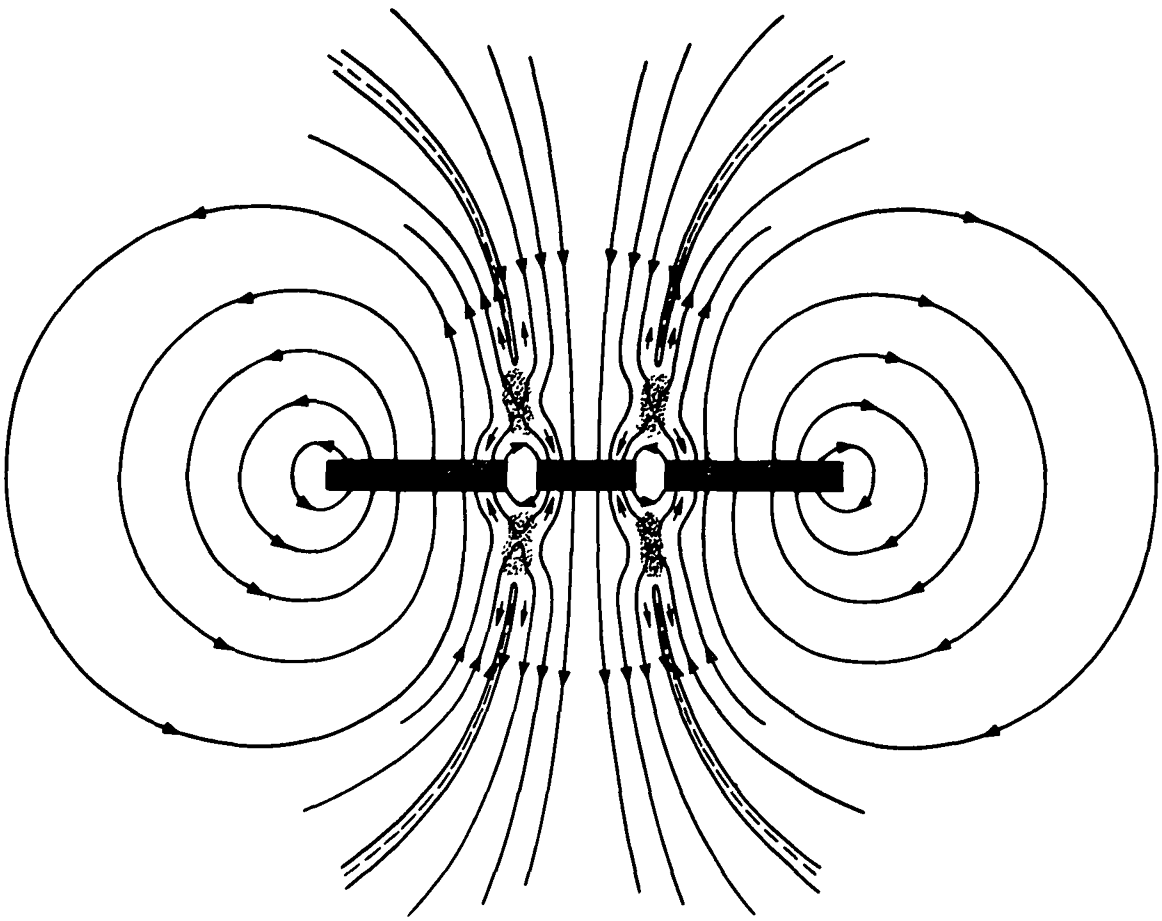

Figure 5

Early stage of galactic flare occurring in magnetoid shown in Figure 4.

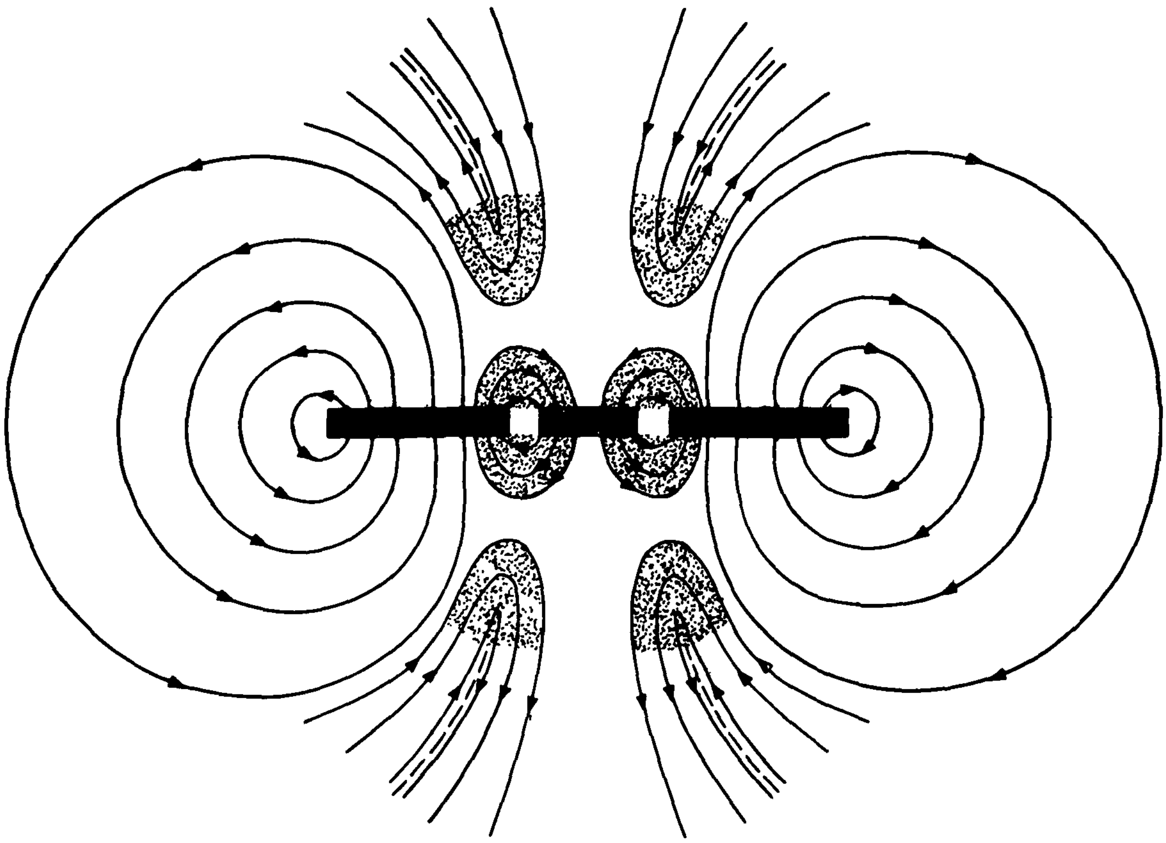

Figure 6

Late stage of galactic flare occurring in magnetoid shown in Figure 4.

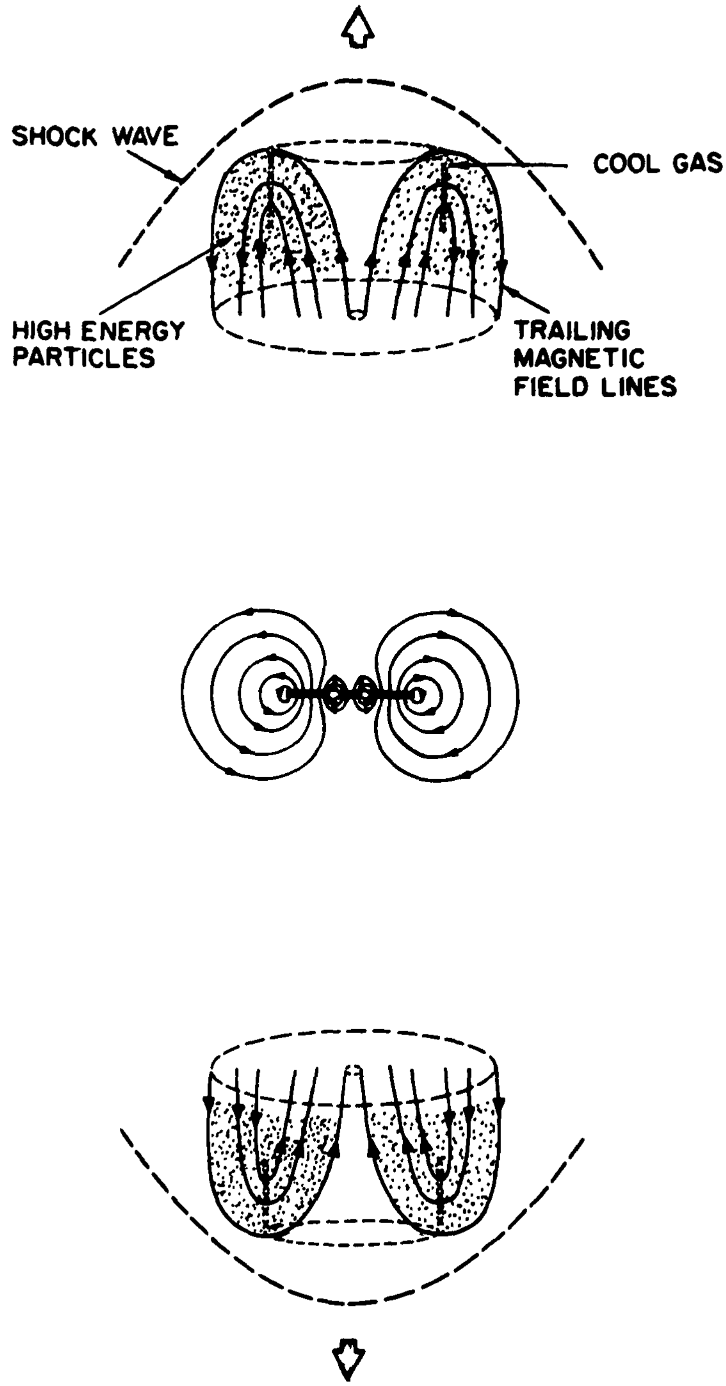

Figure 7

Galactic flare gives rise to ejection of two plasmoids
and returns magnetic field to current-free state.

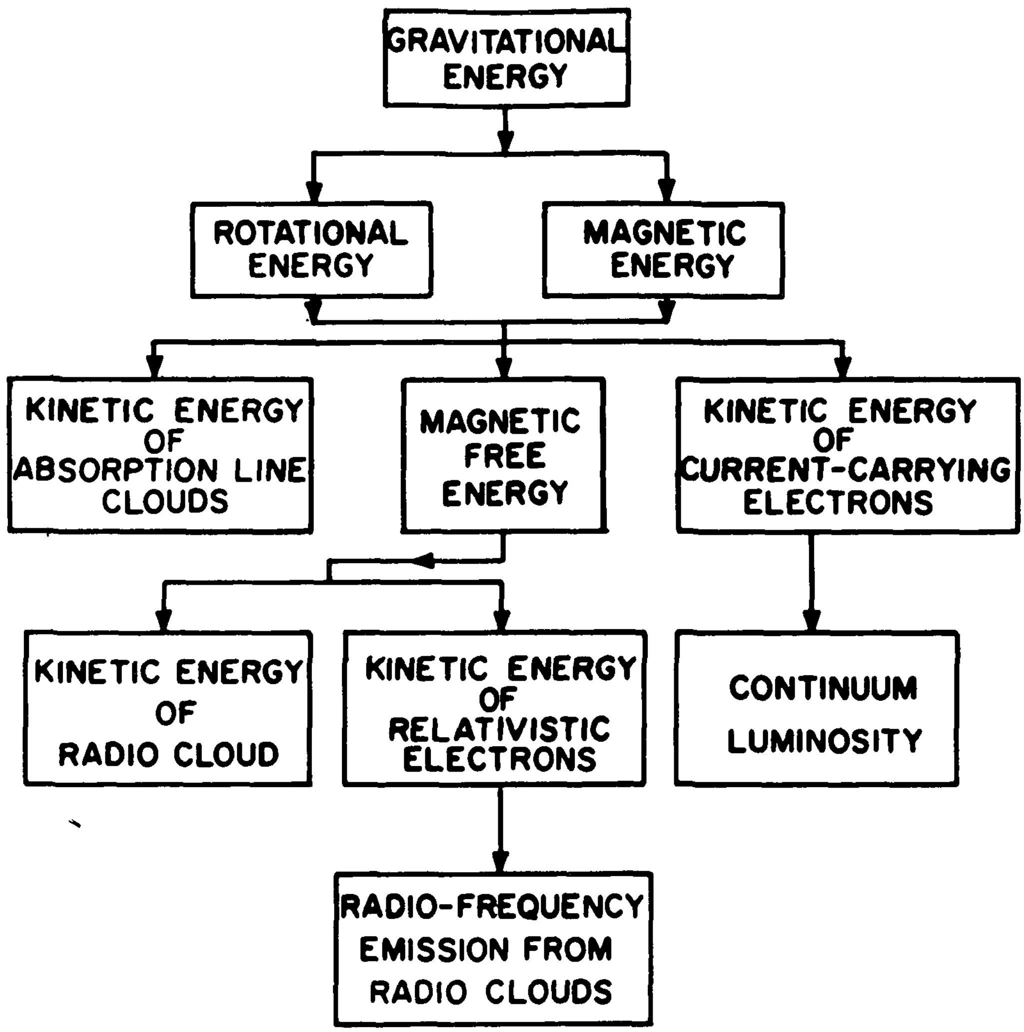

Figure 8

Flow diagram for energy conversion in quasars and active galaxies.