THE ROLE OF ROTATION IN THE CONVERSION OF GRAVITATIONAL ENERGY

P.A. Sturrock
Institute for Plasma Research
Stanford University
Stanford, California

SUMMARY

It is believed that gravitation provides the enormous energies released explosively in quasars (and radio galaxies), and the high nonthermal luminosities of quasars (and Seyfert galaxies). A model of quasars is proposed in which both types of energy conversion take place.

The model comprises a rapidly rotating nucleus in a slowly rotating nebula, the two components being coupled by a magnetic field. Differential rotation leads to the formation of an open-field configuration with current sheets. The open-field pattern leads to an explanation of explosions as "galactic flares", and the current sheets produce the nonthermal luminosity by synchrotron radiation.

1. Introduction

There are only two ultimate sources of energy in astrophysics: nuclear energy and gravitational energy. The most energetic phenomena are believed to draw upon gravitational energy. These phenomena may be divided into two types: continuous and impulsive. Both processes are evident in quasars, which present the most challenging problem of modern astronomy. The best studied quasar, 3C 273, has a total luminosity[1] of 10^{47} erg $\sec^{-1}$, 10^{14} times that of the sun. Furthermore it is known that quasars, like radio galaxies, produce double radio clouds by an explosion mechanism, the total energy sometimes exceeding 10^{60} erg or about 10^{6} $M_{\odot}c^{2}$, where $M_{\odot}$ is the mass of the sun.[2]

In my 1967 essay[3] on explosions in radio galaxies and quasars, I argued that magnetic fields must play an essential role in the conversion of gravitational energy into magnetic energy, but this model could not account for continuous energy conversion in quasars. The aim of the present essay is to argue that rotation must play a key role and that a differentially-rotating object can exhibit both continuous conversion and impulsive conversion of gravitational energy.

It is believed that the Crab pulsar convert rotational energy into electromagnetic energy with high efficiency,[4] and Morrison[5] has suggested that quasars are "giant pulsars". However, theoretical study of pulsars[6] and of Morrison's conjecture[7] leads to the conclusion that a giant pulsar would radiate almost exclusively in gamma rays, and so would not resemble a quasar. Indeed, the comparison summarized in Table 1 shows that quasars more closely resemble x-ray stars than pulsars. The view is developing that x-ray stars comprise a spinning neutron star in a dense surrounding nebula.[8] It is recognized that a spinning neutron star provides an adequate store of energy to provide the luminosity of an x-ray star for many thousands of years, although no precise mechanism has been proposed for converting the rotational energy into the x-ray luminosity. This conjecture, concerning x-ray stars, has recently received confirmation from the discovery that the x-ray emission from Cyg X-1 is periodic with a period of about 73 milliseconds.[9]

For the above reasons, I propose that a quasar comprises a compact rapidly-rotating nucleus surrounded by a massive slowly-rotating nebula, the two parts being linked by a magnetic field.

2. Structure of a Rotating Magnetoid

We consider a spherical object of mass M (gm) and radius R (cm), which we assume to be rotating with period T (sec). Formulas for a uniform sphere show that the moment of inertia is

$$I = \frac{2}{5} MR^2 = 10^{-0.2} MR^2, \qquad (1)$$

so that the rotational energy is

$$W_R = \frac{1}{2} I \omega^2 = 10^{0.9} MR^2 T^{-2}, \qquad (2)$$

and the gravitational binding energy is

$$W_{GB} = \frac{3}{5} GM^2R^{-1} = 10^{-7.4} M^2R^{-1} . \qquad (3)$$

The virial theorem[10] shows that

$$2W_R = W_{GB} , \qquad (4)$$

so that

$$T = 10^{4.3} M^{-1/2} R^{3/2} . \qquad (5)$$

The virial theorem also shows[11] that the possible magnetic flux Φ

(gauss cm^2) is limited by

$$\Phi \equiv \pi R^2 B = \alpha\, 10^{-3} M, \tag{6}$$

where $\alpha \leq 1$. Hence,

$$B = 10^{-3.5} \alpha M R^{-2} . \tag{7}$$

We assume that, by a mechanism to be discussed later, a torque acts on the nucleus, extracting angular momentum and extracting energy at the rate S (erg sec^{-1}). If W_T is the total energy,

$$S = - \frac{dW_T}{dt} = - \frac{d}{dt} (W_R - W_{GB}). \tag{8}$$

On using equation (4), we see that, as energy is extracted, both W_R and W_{GB} increase, the object becoming more compact and spinning more rapidly. The time scale for this process τ (sec) is

$$\tau = \frac{W_T}{S} = 10^{-7.7} M^2 R^{-1} S^{-1}. \tag{9}$$

3. Magnetic Coupling of Nucleus and Nebula; Galactic Flares

We now consider the behavior of the magnetic field coupling the nucleus to the nebula, taking account of differential rotation. For simplicity, we consider the simple axially-symmetric field pattern shown in Figure 1, approximating the nucleus by a dipole and the nebula by a ring dipole. Assuming that the region between the nucleus and the nebula is not a vacuum, magnetic field lines will be "frozen" into this plasma, so that the lines will be stretched by differential rotation. This is an example of a "force-free" magnetic field, some properties of which have been studied elsewhere.[12] From these studies we find that differential rotation will give rise to a "stretching" in the azimuthal direction, and it will also lead to stresses which make the field lines expand away from the nucleus, as shown in Figure 2.

The key property of the present model is the following. As the field is being twisted, energy is being extracted from the rotational energy of the nucleus and converted into magnetic energy. However, only a *finite* amount of energy is required to convert the closed field configuration shown in Figure 1 into the open field pattern shown in Figure 3. Hence, differential rotation through a *finite angle* (of order one rotation) will suffice to convert the closed field pattern of Figure 1 by the open field pattern of Figure 3. The magnetic torque then drops almost to zero and there is no further evolution of the magnetic field pattern. The excess energy, which may be termed "magnetic-free energy", is of order

$$W_{MFE} \approx \frac{1}{8} B^2 R^3 \approx 10^{-7.9} \alpha^2 M^2 R^{-1} . \qquad (10)$$

Since this magnetic energy is associated with current sheets, it may be released by the tearing-mode instability,[13] resulting in a double flare, as shown in Figure 4. The inertia of the ejected plasma cloud soon leads to the configuration shown in Figure 5, in which the plasma cloud is confined by ram pressure, and magnetic field lines trail behind the cloud.[14] It has been shown elsewhere[15] that the properties of this model provide a good fit to the observed properties of radio clouds produced by radio galaxies and quasars. As was shown before,[3] the "galactic-flare" mechanism can explain the high energies associated with radio clouds. The advantage of the present model is that it takes account of rotation of the nucleus and also shows how it is possible for explosions to occur repeatedly in quasars and radio galaxies.

4. Continuum Luminosity of Quasars

It will now be shown that the present model can also explain the continuum luminosity of quasars. To see this we note that current in the current sheets must be carried by electrons which, because of the low density, are likely to be of relativistic energy so that $v \approx c$, though not highly relativistic, since this would not increase the current-carrying capacity of the plasma. If the thickness of the sheet is taken to be b (cm), we see from

$$\nabla \times \vec{B} = 4 \pi \vec{j} , \tag{11}$$

that the current density j is given by

$$j \approx 10^{-0.8} Bb^{-1} . \tag{12}$$

The current density j is related to the electron density n (cm^{-3}) by

$$j = \frac{ne}{c} v \approx ne = 10^{-9.3} n. \tag{13}$$

The total number of electrons N in the "strong-field" region of the current sheets is approximately

$$N = 4 \pi R^2 b n , \tag{14}$$

which, from (12) and (13), becomes

$$N = 10^{9.6} BR^2. \tag{15}$$

We now note that electrons in the current sheet must be moving partly transverse to the magnetic field, as shown in Figure 6, so that they will radiate by the synchrotron mechanism.[16] If the electron energy is E_e (eV), the radiation will peak at the frequency

$$\nu = 10^{-5.3} E_c^{\,2} B \ , \tag{16}$$

and the power emitted per electron is

$$S_1 = 10^{-26.1} E_e^{\,2} B^2 \ . \tag{17}$$

Hence the total luminosity is

$$L = N S_1 = 10^{-16.5} E_e^{\,2} B^3 R^2 \ . \tag{18}$$

We now apply this model to 3C 273. Since this is an extreme case among quasars, we take $\alpha = 10^{-0.5}$ (a large value). We assume that the conjectured 13-year periodicity[17] is real, and so find from equation (5) that

$$MR^{-3} = 10^{-8.6} \ . \tag{19}$$

We note that $\nu = 10^{12.5}$ sec^{-1} at the peak of the spectrum, and that $L = 10^{47}$ erg sec^{-1}. Using (7), (16) and (18), we find that

$$E_e^{\,2} M R^{-2} = 10^{21.8} \ , \tag{20}$$

and

$$E_e^{\,2} M^3 R^{-4} = 10^{75.5} \ . \tag{21}$$

On solving equations (19), (20), and (21) for E_e, M, and R, we find: $E_e = 10^{6.3}$ eV which is, as expected, a mildly relativistic value; $M = 10^{44.5}$ g $= 10^{12.2} M_\odot$; and $R = 10^{17.7}$ cm or 6 light months. Equation (7) shows that $B = 10^{5.1}$ gauss. Hence, from equation (10), the free magnetic energy is $10^{62.4}$ erg, confirming that the model provides ample energy for the production of radio clouds.

5. Discussion

The main results of the preceding sections are summarized in Table 2. As the nucleus contracts, gravitational energy goes partly into rotational energy, due to conservation of angular momentum, and partly into magnetic energy, due to conservation of magnetic flux. Differential rotation of the nucleus and the nebula leads to decoupling of the magnetic fields of each component, with the formation of current sheets. There is then a supply of magnetic free energy, and a large number of high-energy electrons carrying the current. The magnetic free energy can be released by the flare process, in the course of which electrons are accelerated. These high-energy electrons are responsible for subsequent radio-frequency radiation of ejected radio clouds. The model naturally explains the fact that radio clouds typically occur in pairs. The current-carrying electrons give rise to radiation by the synchrotron process and explain the high continuum luminosity of quasars. The steady loss of energy of the current-carrying electrons implies a progressive re-connection of magnetic field lines, and it is this partial re-connection which provides the torque necessary to extract energy from the rotating nucleus. In fact, the "steady state" probably consists of many small-scale stages of decoupling and re-connection, which helps one understand the continual fluctuations in quasar luminosities.[1]

It is well known that solar flares produce high-temperature plasma clouds which produce x-ray emission.[18] These clouds are typically unstable to a thermal instability[19] which leads to the formation of cool, dense condensations which then become visible because of their emission-line radiation. It seems likely that similar processes in the present model will explain the x-ray emission[20] from the quasar 3C 273 and the emission lines which are typical of quasars. Similarly, it is known that solar flares produce many types of radio bursts,[21] and it seems likely that some of these will occur in the quasars on a far more energetic scale.

Although the present model was developed for application to quasars, it may have wider application. Seyfert galaxies[22] have many points of similarity with quasars. They also have bright, massive, compact nucleii. It seems likely that energy conversion in Seyfert galaxies is similar to that in quasars. Finally, it is possible that the model which has been developed for quasars may, on a much reduced scale, provide an acceptable model of x-ray stars. It might then explain both the continuous energy conversion and also the production of twin radio clouds[23] by the x-ray star Sco X-1.

To sum up: it seems that - in pulsars and quasars, and perhaps in x-ray stars and Seyfert galaxies - rotational energy is an interim stage in the conversion of gravitational energy into electromagnetic energy, and that magnetic fields are essential to these conversion processes.

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Table 1

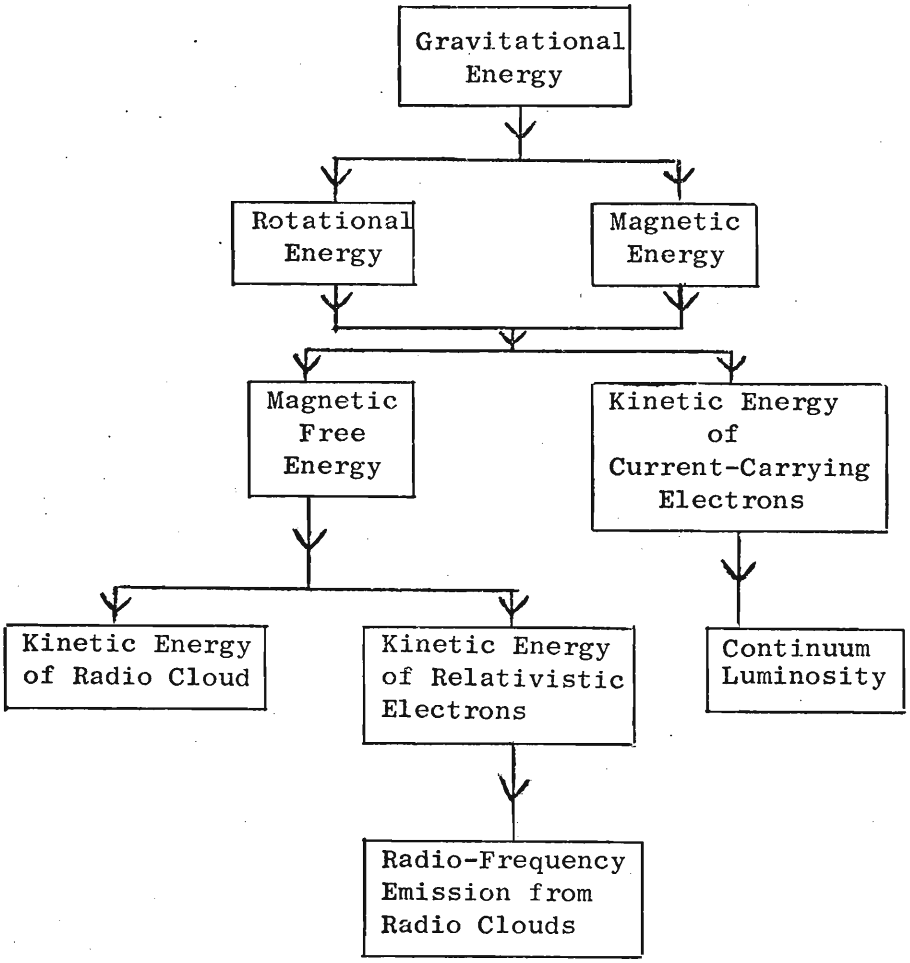
COMPARISON OF OBSERVED PROPERTIES OF PULSARS, QUASARS, AND X-RAY STARS

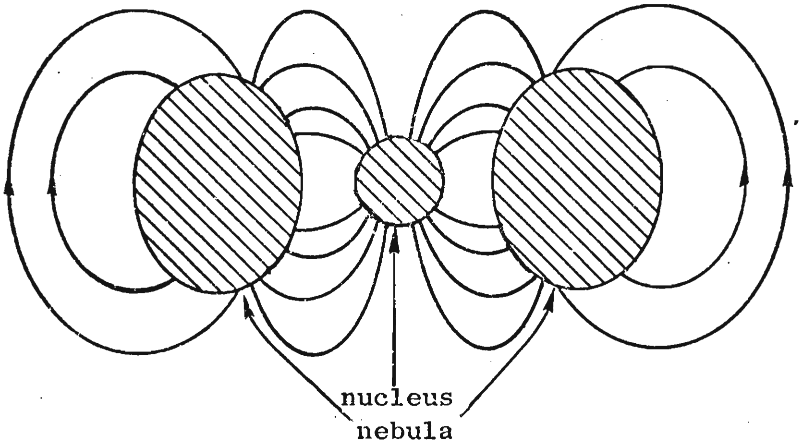
		PULSARS	QUASARS	X-RAY STARS
1.	Radio frequency radiation	All (C). Coherent mechanism	Small fraction. Probably incoherent	Small fraction. Probably incoherent
2.	Optical radiation	One case (Crab Pulsar)	All (C)	All (C)
3.	X-Ray radiation	One case confirmed (Crab Pulsar)	Detected in 3C 273	All (C)
4.	Emission lines	None	All (C)	All
5.	Absorption lines	None	Small fraction	One case (Cyg X-2)
6.	Periodicity	All (C)	One case proposed	One case proposed
7.	Double-ejection of plasma clouds	None	Small fraction	One case

Note. Caption "C" indicates "convection"; these properties are inherent in the definitions of the objects.

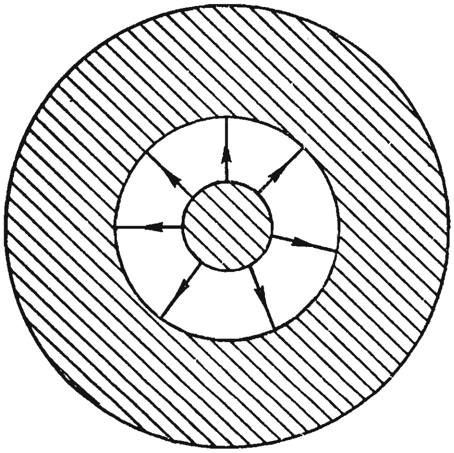
Table 2

FLOW DIAGRAM FOR ENERGY CONVERSION IN QUASARS



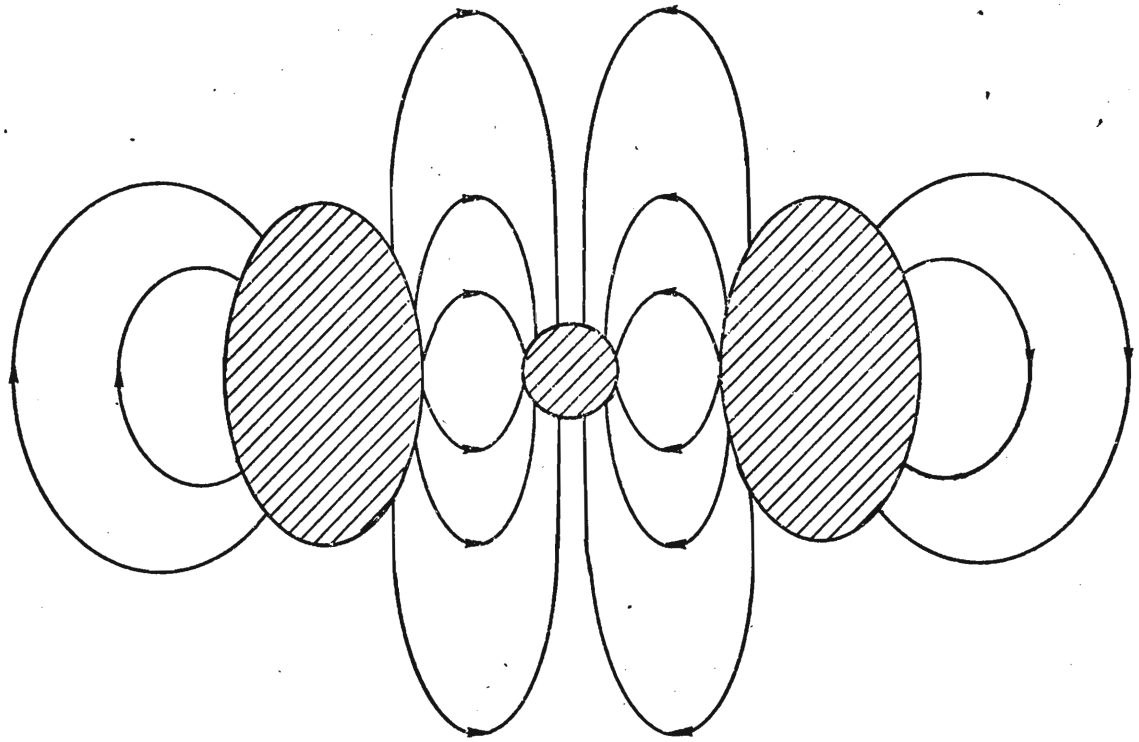


(a) Cross section

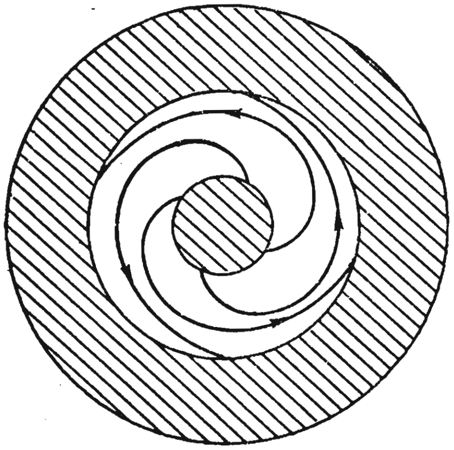


(b) Plan view

Fig. 1. Magnetic field of nucleus and nebula, before differential rotation takes place.



(a) Cross-section



(b) Plan view

Fig. 2. Distortion of magnetic field linking nucleus and nebula due to differential rotation by 180°. (Note that field lines expand away from plane of symmetry.)

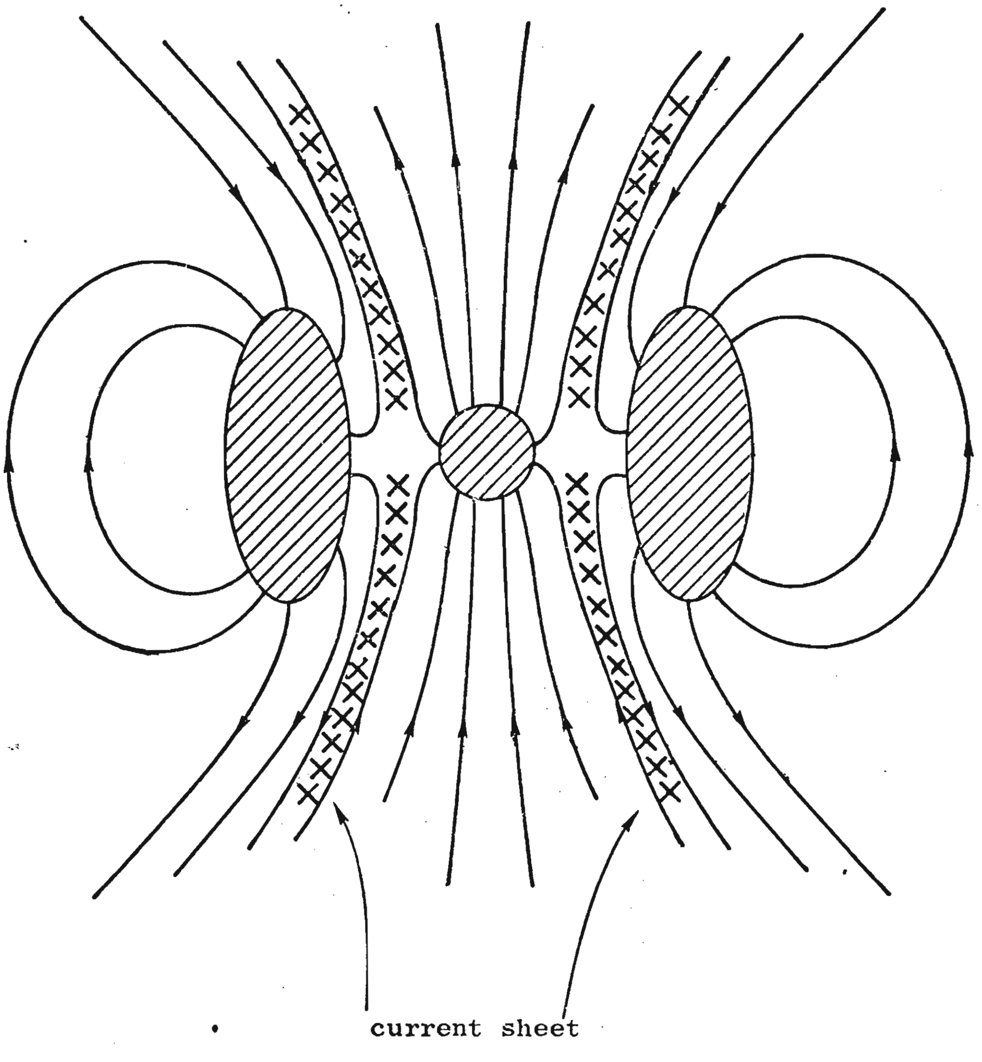


Fig. 3. Cross-section view of magnetic field of nucleus and nebula after differential rotation by 360° or more. Note formation of open-field configuration with conical current sheets.

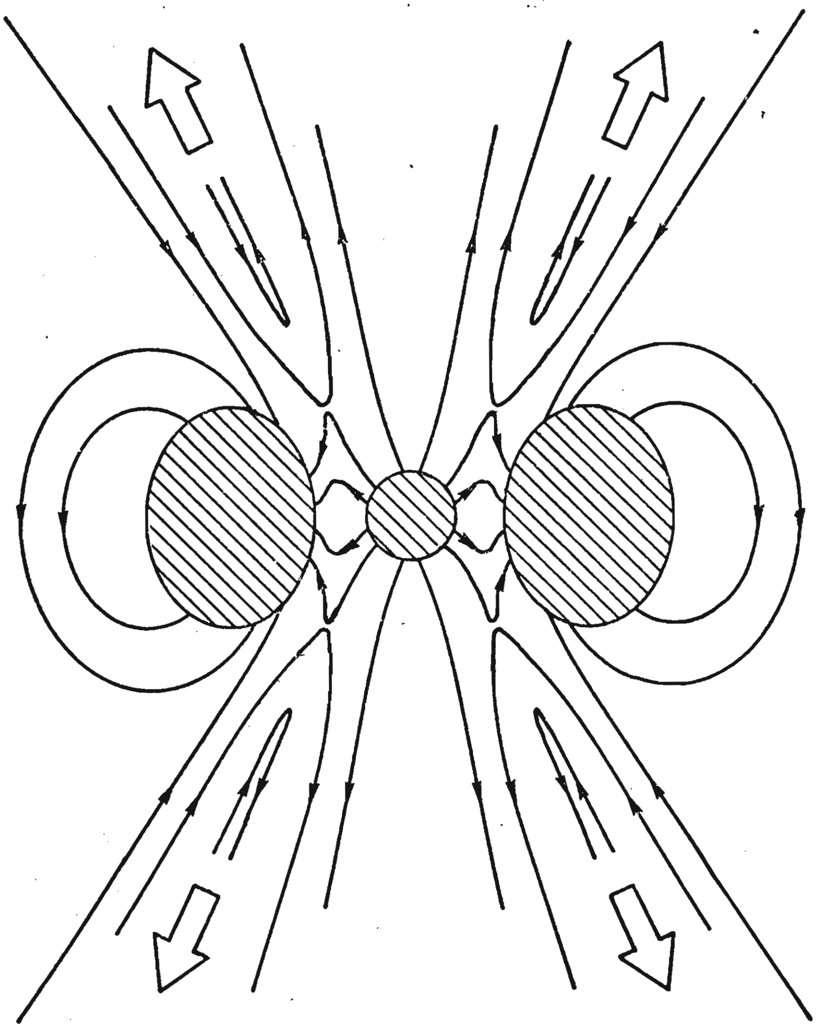


Fig. 4. Field line reconnection (flare) in progress. Plasma ejected by "catapult action" as shown.

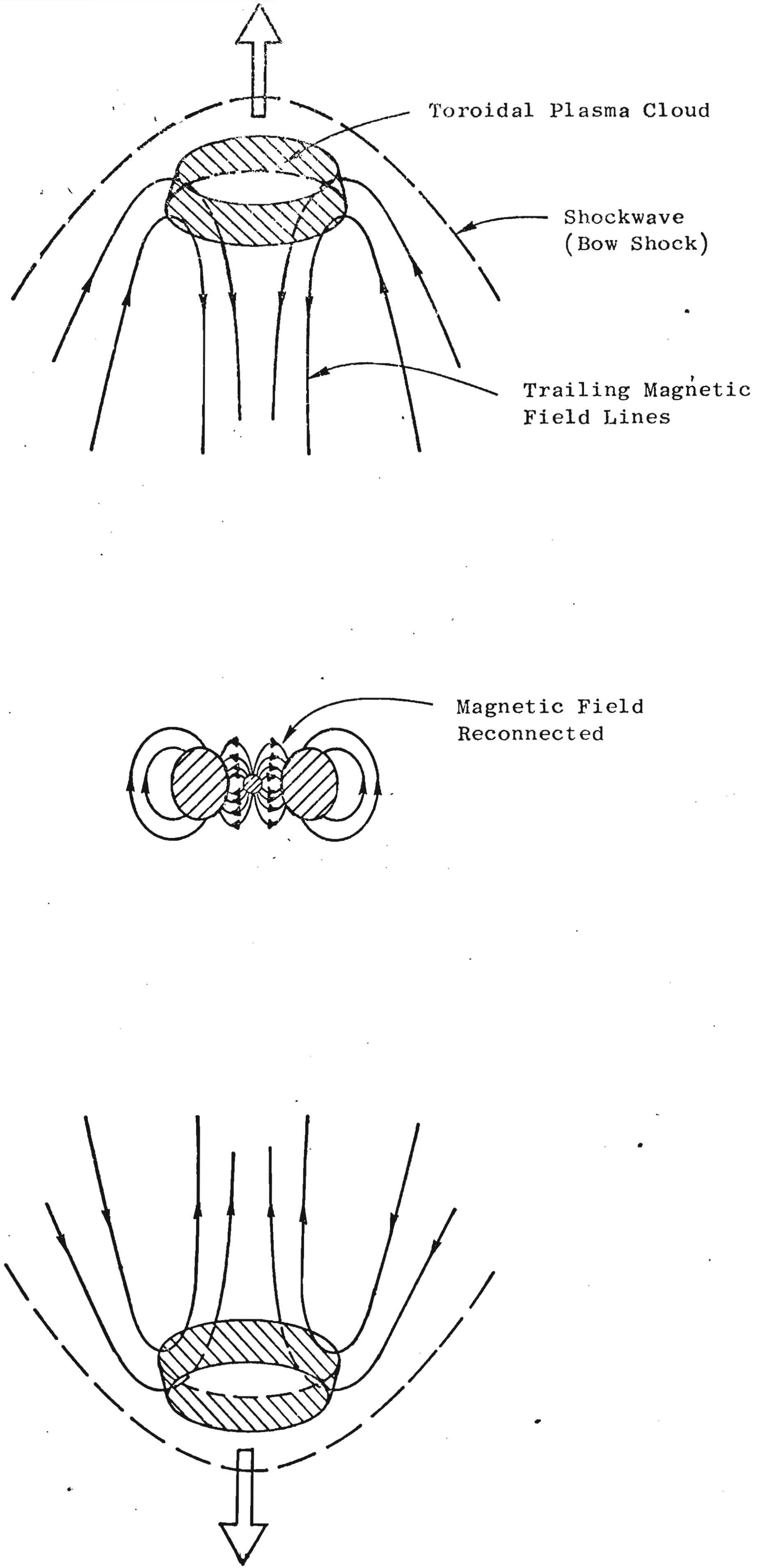


Fig. 5. Plasma-field configuration of plasma clouds (radio clouds) after ejection from quasar by flare action.

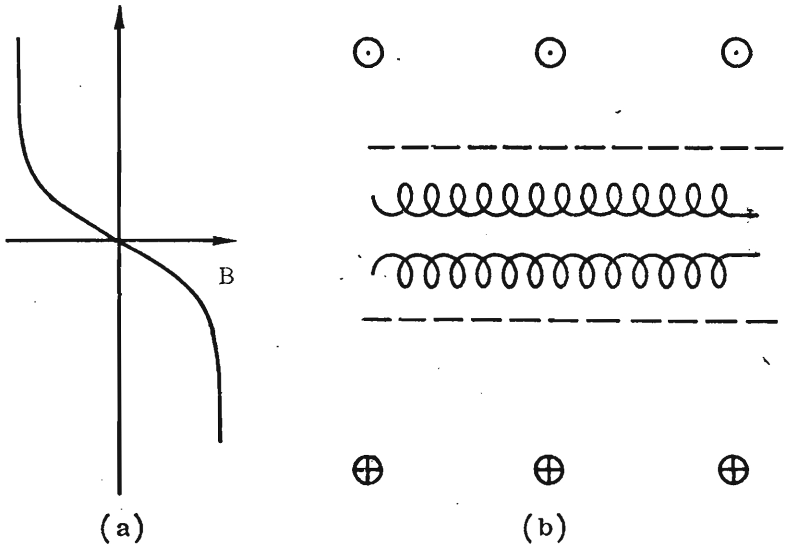


Fig. 6. Electron motion in current sheet.
(a) Variation of magnetic field across current sheet.
(b) Electron motion is a combination of circular motion and drift along the current sheet, due to magnetic-field gradient.

PETER A. STURROCK

Peter A. Sturrock, Professor of Space Science and Astrophysics and Chairman of the Institute for Plasma Research at Stanford University, was born in England in 1924. He studied mathematics at Cambridge University, interrupting his studies to work on radar during the war years, and took his Ph.D. degree in 1951. Since that time he has worked in England, France, Switzerland and the United States on nuclear physics, particle accelerators, microwave tubes, plasma physics and, most recently, space science and astrophysics.

Professor Sturrock is a member of the American Astronomical Society, the American Geophysical Union and the International Astronomical Union, and a fellow of the American Physical Society and Royal Astronomical Society. He was Chairman of the Division of Plasma Physics of the American Physical Society for 1965-66, and Director of the Enrico Fermi International Summer School on "Plasma-Astrophysics" in Varenna, Italy, in July 1966.