

Acceleration on a Galactic Scale

by

P. A. Sturrock

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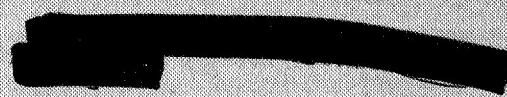
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ABSTRACT

Observations of radio galaxies and of radio emission from quasars provide evidence for particle acceleration on a galactic scale. The acceleration is typically associated with some kind of explosion, i.e., with an instability. It appears, therefore, that galactic acceleration is part of a spontaneous process occurring in a closed system of galactic dimensions. An analogous process on a laboratory scale is provided by certain plasma experiments, in which a quiescent plasma exhibits a sudden "explosive" instability which in turn leads to acceleration of some particles to high energies.

This comparison leads to the suggestion that a galactic explosion which leads to particle acceleration is typically a plasma instability. The form of stored energy most appropriate for this process is that of magnetic energy. If an object condenses out of intergalactic gas permeated by a magnetic field, some of the gravitational energy lost during condensation will be converted into magnetic energy, since the magnetic field will be compressed. In the absence of anomalous processes, the magnetic field must remain connected with the intergalactic field, so that the resulting field configuration will not be current-free and therefore not in its lowest energy state. It appears that the currents will be confined to certain sheets which comprise "sheet pinches." The tearing-mode resistive instability provides a mechanism for releasing the excess magnetic energy. This process is believed to be the same as that of solar flares, so that explosions in radio galaxies and quasars may be "galactic flares."

Various forms are suggested for the magnetic-field configuration to be associated with a newly condensed object with the mass of a galactic nucleus, tentatively identified as a quasar, and an evolved radio galaxy. The energy content of such configurations is estimated, and shown to be adequate to explain observed radio clouds.

Discussion of a radio outburst of 3C 273 leads to the view that some of the radio emission from quasars is the result of collective plasma processes. Hence such outbursts provide direct evidence for the occurrence of plasma instabilities on a galactic scale.

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ACCELERATION ON A GALACTIC SCALE

We have, broadly speaking, two sources of information concerning high-energy particles on a galactic scale (the scale of our own galaxy or of extra-galactic galaxies). These are our observations of cosmic rays,¹ that is, of high-energy ions, and of the radio emission which is generally ascribed to synchrotron radiation from high-energy electrons.² Although we are accumulating quite detailed information about cosmic rays, it is my view that we have much more detailed information about high-energy electrons, through radio observations. We know, in many cases, which objects of galactic dimensions are responsible for the acceleration. In some cases, we can observe the polarization³ of the radio emission and so obtain information about the magnetic field structure. We can obtain the radio spectrum and so infer the particle spectrum.⁴ We may make estimates of the physical dimensions of the regions occupied by high-energy electrons.⁵

For these reasons, it seems to me that anyone who wishes to understand acceleration of particles in nature should begin by trying to understand electron acceleration. In any case, it seems sensible that I should concern myself with electron acceleration since the next two speakers will both be concerned with the origin of cosmic rays.

The "canonical form" for the radio emission from a radio galaxy is that of two radio clouds symmetrically placed with respect to the galaxy (Fig. 1). These radio clouds have all the appearance of being "smoke" from some kind of explosion. The question with which we are concerned may be interpreted as that of determining what kind of fire gives rise to this kind of smoke. In order to test an answer to this question, it will be necessary to set up a model of what goes on in order to be able to make appropriate calculations. The model will doubtless be so complex as to involve a chain of calculations, and we should bear in mind that the strength of the entire chain is the strength of the weakest member.

It is instructive to look for an analogy for the galactic acceleration process. We might think first of man-made accelerators, but this is a bad analogy. Accelerators must be hooked up to a power line since they require a high-grade energy input. It does not seem reasonable

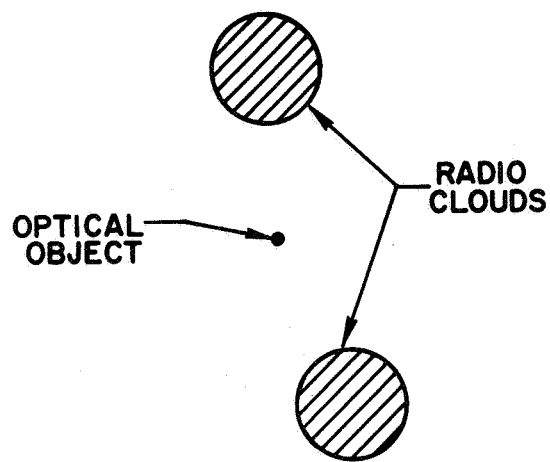


FIG. 1. TYPICAL STRUCTURE OF RADIO GALAXY.

to assume that, when a radio galaxy "explodes," it receives a sudden burst of high-grade energy from intergalactic space. It is more reasonable to regard the galaxy (at least, for the explosion process) as a closed system. It appears that the energy conversion which takes place in this closed system is spasmodic. In this regard, the explosion is like a solar flare.^{6,7} It is my view that a solar flare is an excellent analogy to galactic explosions,^{8,9} and this is a point to which we shall return later on.

It is desirable to find an even simpler analogy for which we have more certain understanding. We might, therefore, look for a laboratory example of a closed system which gives rise to spasmodic particle acceleration. Such phenomena are observed in plasma laboratories. An excellent example was recently reported by Baidorodov, Gott, Ioffe, and Yushmanov.¹⁰ A highly simplified characterization of their device is shown in Fig. 2; it is a magnetic bottle containing trapped plasma. By an ingenious field configuration which is not indicated, the system is made to be stable against certain macroscopic instabilities so that there is only a slow loss of particles.

Figure 3 is a reproduction of some of the data. After some initial adjustments which do not concern us, the device typically settles into a quasi-steady state in which the plasma decays with a time scale of about one millisecond, as shown in the top curve. The density is measured by the charge-exchange flux.

It was observed that sometimes the density drops very sharply. When this occurs, there is a rapid loss of ions to the walls, the plasma traveling primarily along the field lines. This is shown in the second curve. The third curve of Fig. 3 shows the response of a detector of high-energy particles. It is found that there is a sudden flux of particles of energy in excess of 30 keV (far higher than the thermal energy of the initial plasma), the flux beginning at the time of the sudden loss of plasma from the magnetic bottle. A loop antenna registers a burst of electromagnetic radiation, as indicated in the fourth curve of Fig. 3, the duration of which (15 to 20 μ sec) and the timing of which agree well with those of the drop in density.

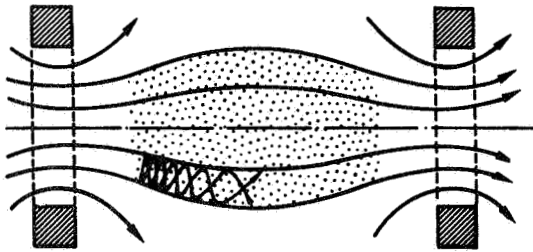


FIG. 2. SCHEMATIC DIAGRAM OF PLASMA DEVICE WHICH EXHIBITS SPONTANEOUS ACCELERATION.

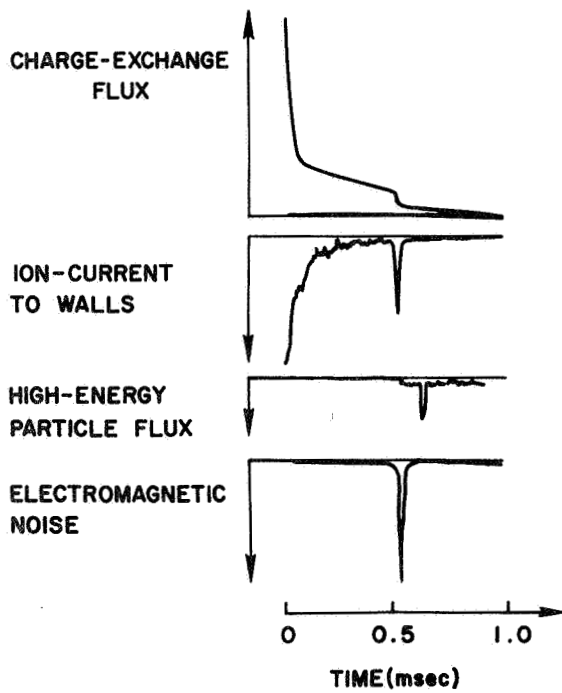


FIG. 3. EXPERIMENTAL RESULTS OBTAINED WITH PLASMA EXPERIMENT.

I think that this simple example is very instructive, and I will go so far as to say that it offers a prototype of what we must look for when we are trying to understand acceleration of particles in nature. First, we must look for some kind of stored (and available) energy. In this experiment, the stored energy is due to a "double-humped" energy distribution. Second, we must look for an instability which provides a mechanism for the release of the stored energy. Third, this instability must give rise to electromagnetic fluctuations of nonthermal amplitude (rather than to, say, low-velocity bulk motion). Fourth, these electromagnetic fluctuations must accelerate a small fraction of the particles to high energies.

Rather than use this experiment as a prototype, one might prefer to reverse the chain of argument. One would then say that the acceleration of particles requires a nonthermal spectrum of electromagnetic fields. This must be produced by some kind of instability. In order to have an instability, one must have some kind of stored energy. The type of instability best suited for the generation of electromagnetic noise is a plasma instability.

Let us now consider the acceleration of particles by a nonthermal electromagnetic field. In one form or another, this type of acceleration process has been favored for many years, since it was first clearly proposed by Fermi.^{11,12} The basic idea is represented by the following equation¹³

$$\frac{\partial f}{\partial t} = - \frac{\partial}{\partial w} \left(\left\langle \frac{\Delta w}{\Delta t} \right\rangle f \right) + \frac{1}{2} \frac{\partial^2}{\partial w^2} \left(\left\langle \frac{\Delta w^2}{\Delta t} \right\rangle f \right), \quad (1)$$

where w is the particle energy and $f(w,t)$ is the energy distribution function. In the "weak-fluctuation" approximation, the cumulative effects of the random fields may be represented by the above Fokker-Planck equation. $\langle \Delta w / \Delta t \rangle$ is the mean rate of gain of energy, and $\langle \Delta w^2 / \Delta t \rangle$ is an energy diffusion term which is required in the general form, but which did not appear in Fermi's original presentation. If the energy gain is proportional to energy,

$$\left\langle \frac{\Delta w}{\Delta t} \right\rangle = \alpha w \quad (2)$$

and if there is a loss term which is independent of energy, the equation takes the following form

$$\frac{\partial f}{\partial t} = - \frac{\partial}{\partial w} (\alpha w f) - \nu f . \quad (3)$$

The steady-state solution of this equation has a power-law form:

$$f = c w^{-(1 + \nu/\alpha)} . \quad (4)$$

Many variants of the type of calculation first proposed by Fermi are now in the literature.^{14,15} As a result of laboratory experiments of the type described earlier, a very powerful technique has recently been developed, based on the description of the electromagnetic field as a stationary random distribution. That is, the electromagnetic field is regarded as "turbulent."¹⁸

The basic idea and method may be illustrated by a very simple example, that of the nonrelativistic motion of charged particles in one-dimension in a purely electric field.¹⁹ We now introduce the velocity distribution function $f(v,t)$, which satisfies the Fokker-Planck equation

$$\frac{\partial f}{\partial t} = - \frac{\partial}{\partial v} \left(\left\langle \frac{\Delta v}{\Delta t} \right\rangle f \right) + \frac{1}{2} \frac{\partial^2}{\partial v^2} \left(\left\langle \frac{\Delta v^2}{\Delta t} \right\rangle f \right) . \quad (5)$$

The equation of motion is

$$\frac{d^2 z}{dt^2} = \frac{dv}{dt} = \frac{q}{m} E_z(z,t) . \quad (6)$$

Assuming that the mean electric field is zero

$$\langle E_z \rangle = 0 ,$$

The field is described to lowest order by the correlation function

$$R(\xi, \tau) = \langle E_z(z, t) E_z(z + \xi, t + \tau) \rangle . \quad (8)$$

With an appropriate multiplying factor, the Fourier transform $W(k, \omega)$ of the correlation function

$$R(\xi, \tau) = 8\pi \iint dk d\omega e^{i(k\xi - \omega\tau)} W(k, \omega) \quad (9)$$

gives us the energy spectrum of the field, analyzed in both wave number and frequency,

$$W_T = \frac{1}{8\pi} \langle E_z^2 \rangle = \iint dk d\omega W(k, \omega) . \quad (10)$$

It is a straightforward matter to compute orbits in this random field and so evaluate the coefficients of the Fokker-Planck equation. If we do this, we find that Eq. (1) reduces to the form of a diffusion equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial v} \left[D(v) \frac{\partial f}{\partial v} \right] \quad (11)$$

where

$$D(v) = 8\pi^2 \frac{q^2}{m} \int dk W(k, vk) . \quad (12)$$

This represents an integration of the energy spectrum over all waves with phase velocities equal to the particle velocity.

If the spectrum should be flat over the range of wave numbers and frequencies of interest, so that D is independent of v over some range of velocities, then the asymptotic solution of Eq. (11) is a Maxwellian distribution, the temperature increasing linearly with time.¹⁹ This shows that this stochastic process does indeed lead to acceleration. However, if the energy spectrum is power-law in form, the diffusion coefficient also is power-law in form, and we find that the stationary solution of the diffusion Eq. (11) leads to a velocity spectrum which is a power-law. This fact, which appears to be true for any stochastic

acceleration mechanism, indicates that we are on the right track. The particle spectrum will tend to a power-law form if the turbulence spectrum tends to a power-law form. We know from the universal theory of turbulence²⁰ that a power-law is a natural asymptotic form for the spectrum, and there is reason to believe that the same will hold true of magnetohydrodynamic turbulence also. These possibilities are currently being explored at Stanford University.

It must be emphasized that there are many variants of the process sketched so briefly in the preceding paragraphs. The electromagnetic fluctuations may be composed of plasma oscillations, Alfvén waves, acoustic waves, or some of the more complicated wave types which arise in plasma physics.²¹ The acceleration may be due to a component of electric field parallel to the magnetic field, to a low frequency component produced by induction, or to a transverse electric field with frequencies comparable with the gyrofrequency of high-energy particles, such as may be produced by a spectrum of Alfvén waves.²²

In this context, it is important to note that where there is acceleration there is also damping. The energy given to the particles is taken from the waves. The type of wave damping caused by stochastic acceleration appears to be identical¹⁹ with what has been called "Landau" damping²³ in plasma physics. It follows that an effective acceleration mechanism must involve a selection process. The field must not accelerate all particles indiscriminately. It is necessary to make the rich richer and keep the poor poor. In discussing the acceleration of electrons, one such selection process is provided by Coulomb collisions, which implies that only electrons of a certain critical energy "run away" and acquire arbitrarily high energy. Electrons below this critical energy belong to the "thermal" part of the distribution. This process was analyzed some time ago by Dreicer.²⁴

If acceleration is indeed due to a low-frequency electric field parallel to the magnetic field, the selection mechanism being that of the runaway process, practically no energy would be put into ion acceleration since the critical energy for ions is very much higher than that for electrons. Hence, if one believes that the acceleration of ions (as

evidenced by cosmic rays) is somehow connected with the acceleration of electrons, it is essential to find some other acceleration and selection

mechanisms. The latter may possibly be a gyroradius effect, the wave spectrum being such that particles of small gyroradius are not accelerated, but those of large gyroradius are accelerated. Such a process would appear at first sight to put most of the available energy into ions rather than electrons, but whether or not this is the case depends on the detailed electromagnetic field spectrum.

Let us make a very simple calculation to see how effective such a process is likely to be in a context of interest to us. Greenstein and Schmidt²⁵ estimate the magnetic field in the jet of 3C 273 to be about 4×10^{-5} gauss. (Our conclusion does not depend very critically on this estimate.) Suppose that the fluctuations in the magnetic field have an amplitude of one percent of the average value, that is 4×10^{-7} gauss. Suppose, furthermore, that the density of thermal particles is about 10^{-4} cm^{-3} ; then the Alfvén speed is about 10^9 cm sec^{-1} . This means that the random electric field is of amplitude 10^{-8} esu or $3 \times 10^{-6} \text{ V cm}^{-1}$. If we take the mean free path for the random process to be equal to the gyroradius of a 10^{12} eV electron, i.e. 10^{14} cm corresponding to a "collision time" of $3 \times 10^3 \text{ sec}$, we find that there are about 10^9 steps in the random-walk process (adopting a lifetime of 10^5 years for the jet) and that the energy gained or lost per step is about $3 \times 10^8 \text{ eV}$. The average increase of energy of particles subjected to this process is therefore about 10^{13} eV , which is somewhat greater than the value of $2 \times 10^{12} \text{ eV}$ needed to explain synchrotron radiation in the visible part of the spectrum. We see then that although the acceleration process is random in character, it may be quite efficient for our purposes.

In order to pursue our chain of argument, it may be necessary to determine the turbulent spectrum. This means that we must determine the origin of the fluctuations, which is another way of saying that we must know the nature of the instability. At this point, it seems appropriate for us to take a small detour from the main line of our argument to ask whether there is any evidence that any plasma instability ever occurs on a galactic scale. I believe that evidence for such an occurrence is

given by data recently published by Pauliny-Toth and Kellermann^{26,27} concerning a centimeter-wave radio outburst of 3C 273. The relevant data are reproduced in Fig. 4. As you see, there is a sudden increase in brightness at 2 cm by a factor of two in only a few months.

Since synchrotron radiation theory has been so successful for so long, one immediately tries to interpret these results in terms of this process. However, this leads to some difficulties. The linear scale of the region responsible for the outburst must be less than a few light months in dimension, so that it is reasonable to require that the radius of the volume (assumed spherical) is not more than 3×10^{17} cm. The maximum intensity of the radio emission during the outburst reaches 70 flux units. If 3C 273 is at its "cosmological" distance of 470 Mpc, a simple calculation shows that the brightness temperature of the source exceeds 3×10^{13} °K. If this radiation is due to a single-particle process, the particles producing the radiation must therefore have an energy in excess of 3×10^9 eV. Assuming now that the radiation is due to electron synchrotron radiation, and noting that the radiation is peaked at 2 cm wavelength, we see²⁸ that the magnetic field has a strength which must not exceed 3×10^{-4} gauss. In order to explain the total intensity, there must be an average density of 4×10^3 cm⁻³ of particles of energy 3×10^9 eV. However, this implies that the gas pressure exceeds the magnetic pressure by a factor of about 10^9 . We also find that the radiation lifetime of the system is 300 y, whereas the burst lasts only a few months. Worst of all, we find that the rf magnetic field strength of the radio waves amounts to 3 gauss, 10^4 times the assumed dc magnetic field strength. This implies that the inverse-Compton process²⁹ is 10^8 times more effective than the synchrotron process, so that it is completely inconsistent to interpret the radiation as due to the synchrotron mechanism. One might try to salvage the synchrotron-radiation mechanism by considering the possibility that the radiation is due to protons, but this hypothesis also runs into difficulties. Protons of energy 3×10^9 eV must be in a magnetic field of strength 10^6 gauss in order to radiate at 2 cm. The radiation lifetime would be about right, 4 months, but the total energy in the magnetic field would be equivalent to the rest mass

energy of about 4×10^7 M. This energy problem could be alleviated by considering that the emission then comes from a volume much smaller than that indicated by the duration of the outburst, but in any case one faces the problem that the electron gas will have a very high absorption coefficient so that, although the energy may originate from protons, the rate at which energy can escape will be determined by the electrons.

These considerations strongly suggest that the radiation leading to such an outburst is not due to a single-particle mechanism. The fact that the radiation of the outburst has a fairly narrow spectrum also argues strongly against a synchrotron-type interpretation.

If the radiation is not due to a single-particle mechanism, it must be due to a bunched-particle mechanism.³⁰ In this case, the high brightness temperatures do not imply that the individual particles have correspondingly high energy. Type I and Type III radio bursts from the sun³¹ and Jupiter's radio bursts³² all have brightness temperatures comparable with the value quoted for 3C 273. However, if particles are bunched, there is a reason for it. There must be a plasma instability which has caused the particles to bunch. We see then that observation of radio outbursts of the type just described provide fairly direct evidence that plasma instabilities do occur in objects of galactic dimensions.

Now that we have a general idea of the sequence of steps which can lead to particle acceleration, you may ask whether one can propose a specific model which meets these requirements. In the second part of this lecture, I wish to propose such a model.

Since our aim is to identify certain plasma mechanisms, it is most important that we try to form an idea of the strength and configuration of the magnetic field. We may obtain some insight into this by remembering the typical radio cloud structure shown in Fig. 1. There are typically two radio clouds which are symmetrically placed with respect to the central object.

If, as is widely believed, the radiation is produced by the synchrotron mechanism, each cloud must contain high-energy electrons and magnetic field. If the high-energy electrons were produced during the explosion which occurred in the vicinity of the central object, the magnetic field

also must have come from the same neighborhood. The reason for this is that, to very close approximation, the magnetic field must move with the plasma. For instance, reference to the Equation (2.38) of Spitzer³³ shows that, if a radio cloud has dimensions of about 10 kpc, the time scale for relative diffusion of plasma and magnetic field is in excess of 10^{30} y. We see that the magnetic field pattern must be now (at the time of observation) or at some time in the past (prior to the explosion) as shown in Fig. 5. Hence, the magnetic flux which now goes through a radio cloud must at one time have passed through (or close to) the central object. This implies that the magnetic flux threading the central object must be at least as great as the magnetic flux in either radio cloud. If we refer to the virial theorem,³⁴ we find that a lower limit to the magnetic flux leads to a lower limit to the mass of the central object. This inequality is

$$M > 10^3 \Phi \quad (13)$$

where M is in grams and Φ is in gauss cm^2 . If we have a measurement of the size of the central object, or perhaps an upper limit to the size, we may estimate the strength of the magnetic field threading the central object.

We may consider as an example the radio galaxy Virgo A.³⁵ The magnetic flux through each radio cloud has been estimated to be 2×10^{42} gauss cm^2 . There is admittedly some uncertainty in this estimate, since it is based on the supposition that the magnetic energy and the particle energy in the radio clouds are equal. This estimate of the magnetic flux implies that the central mass must exceed $10^{12} M$. If this mass is identified with the whole galaxy, we find that the magnetic field strength must be of order 10^{-3} gauss and that the total magnetic energy is approximately 10^{61} ergs. If the flux threads through the nucleus (this would then be a very massive nucleus), the magnetic field strength is increased to 5×10^{-2} gauss and the magnetic energy to 5×10^{61} ergs.

If one applies similar considerations to quasi-stellar objects, one is led to very much higher magnetic field strengths,⁹ since the magnetic

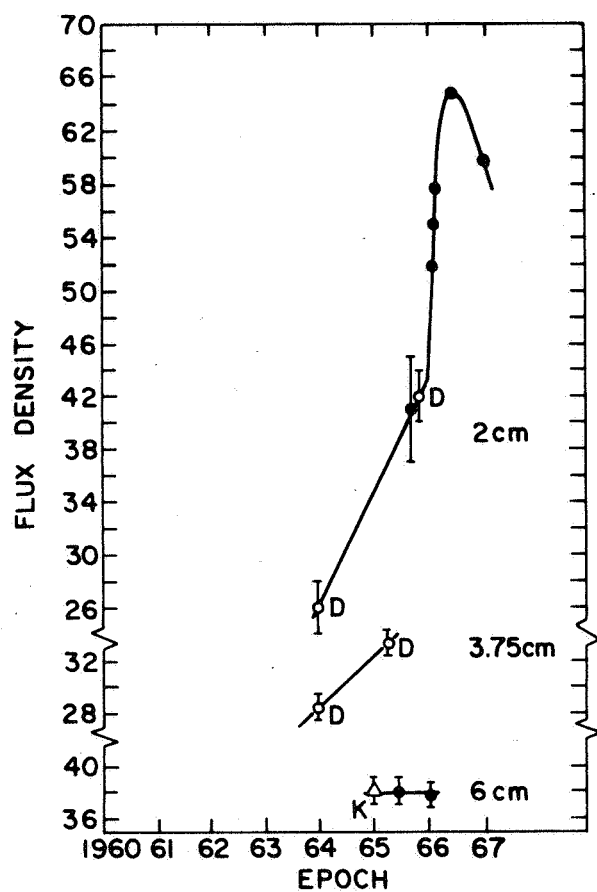


FIG. 4. RADIO OUTBURST OF 3C 273.

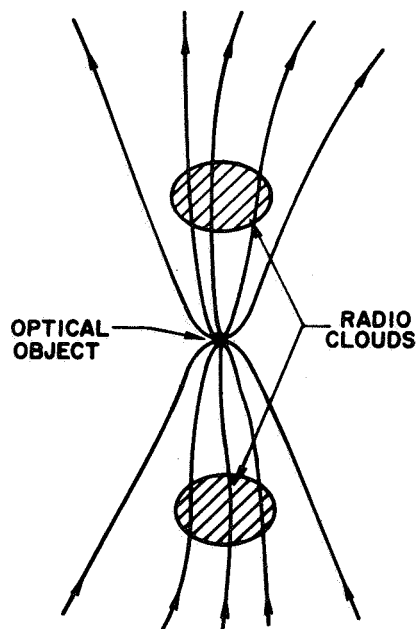


FIG. 5. SCHEMATIC VERSION OF POSSIBLE TOPOLOGY OF MAGNETIC FIELD ASSOCIATED WITH RADIO GALAXY.

flux through the radio cloud is comparable with that of a radio galaxy, whereas the size of the central object is very much smaller than that of the radio galaxy. An analysis of 3C 273 along these lines,³⁴ which assumes that the object is at cosmological distances and obtains information about the dimensions of the central object from the apparent periodicity of the light curve,³⁶ leads to estimates of the central magnetic field strength in excess of 10^6 gauss. Although the strength of the magnetic field is very high, it should be emphasized that the total flux is in fact less than that of Virgo A, being only 2×10^{38} gauss cm^2 through the optical object. The magnetic energy associated with this model would be 3×10^{59} ergs. It is clear that a magnetic field of this magnitude will have an important effect on the structure and stability of such an object, but these are questions which we cannot pursue at this time. A brief discussion is given in Ref. 34 and an independent and more detailed treatment has been presented by Ozernoy.³⁷

Once we face up to the existence of a magnetic field in the central object, the inevitable question is, "What is its origin"? In considering stellar magnetic fields, one appears to have the choice of interpreting the field as a "fossil," or interpreting the field as produced by either dynamo or battery action.³⁸ Since the galactic scale is so much larger than the stellar scale, the time scale for either dynamo or battery action is very much greater than it would be in a star. If this is so, the magnetic field which threads a quasar or radio galaxy must be primeval in origin. We may make a simple estimate of the required strength of the primeval magnetic field by expanding a radio galaxy such as Virgo A until its mean density returns to its original value, that of intergalactic gas. If this is assumed to be $10^{-29} \text{ g cm}^{-3}$, we find that we require an intergalactic magnetic field of about 5×10^{-8} gauss.

Let us now consider in a little more detail what would happen to a primeval magnetic field when an object condenses from intergalactic gas. As long as there is any significant degree of ionization, the magnetic field is "frozen" into the plasma and condenses with it, so that the connection of the magnetic field to intergalactic space and to the condensing mass is preserved. Hence, when a massive object has condensed,

the magnetic field configuration will be something like that shown in Figure 6.

This particular field configuration is based on the supposition that there is strict cylindrical symmetry about the magnetic field direction, and that the system possesses no angular momentum. This assumption may not be as bad as it seems at first sight, since this model has a built-in way of getting rid of angular momentum. As long as the speed with which gas streams into the central object is less than the local Alfvén speed, the magnetic field can "propagate" angular momentum away from the condensing gas back to intergalactic space. This fact enables us to explain the formation of such complex objects as quasi-stellar objects and the dense nuclei of some galaxies.

Another important point to note is that, if the mass density drops rapidly outside the central object, there will in general be a surface of sharp field reversal, what is known in plasma physics as a "sheet pinch."³⁹ Since only a finite amount of flux can be connected with the central object, the sheet pinch can extend only a finite distance. The termination of the sheet pinch will have the form of a Y-type neutral line. The field lines outside this neutral line have such a curvature that they form a trap for accreting gas. This is likely to be the region of lowest Alfvén velocity, so that this is where the "angular-momentum-propagation" mechanism will fail first. It therefore seems likely that the main body of a galaxy will develop from this region.

It appears from its role in the geo-magnetic tail⁴⁰ and in solar flares⁸ that a sheet pinch is metastable; this is highly significant. A configuration which is totally unstable would be of no interest to us, since it could never exist. Furthermore, a configuration which is totally stable would be of no interest, since it would never release any energy. A configuration which is metastable can store a finite amount of energy, and then release this energy in an explosive way.⁴¹

It is appropriate here to spend a little time discussing solar flares. This phenomenon has been studied for many years, and astrophysicists have long realized that the instability manifested as a flare must be a plasma instability and that the stored energy released by the

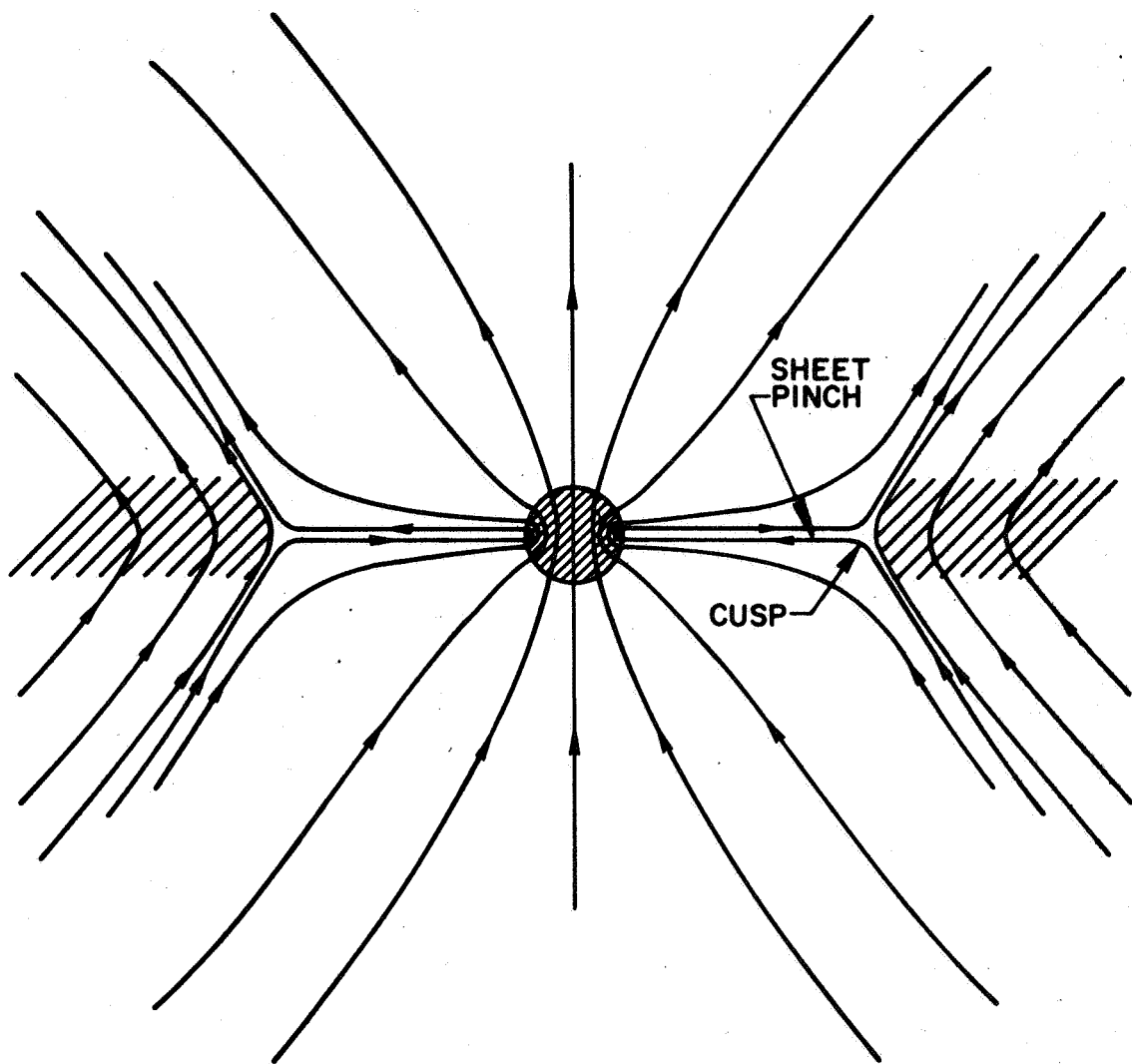


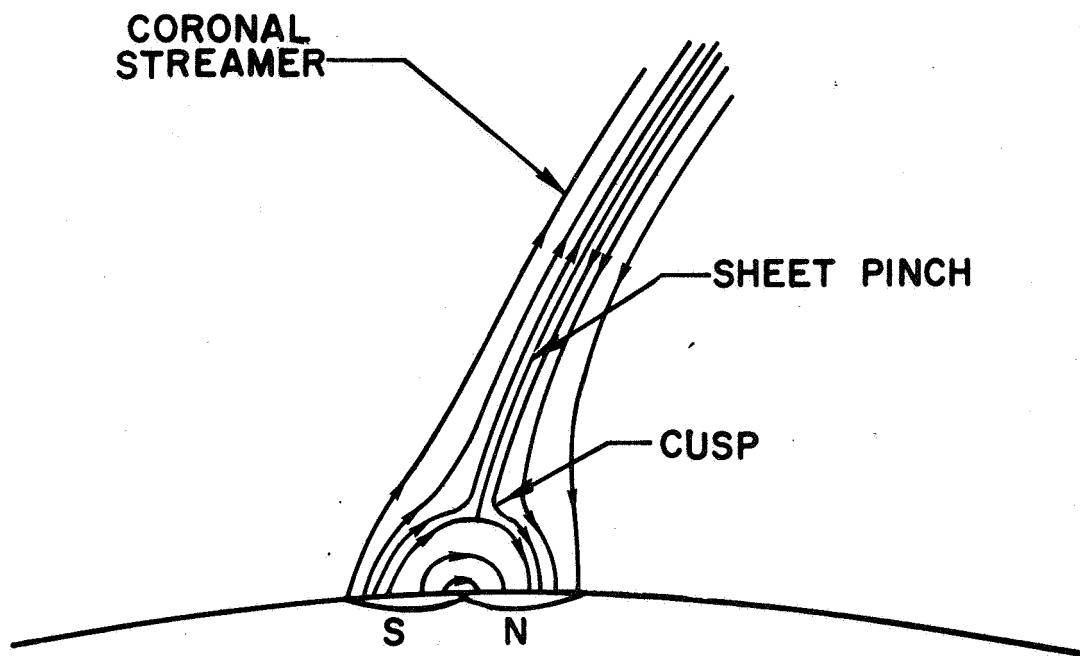
FIG. 6. PROPOSED MAGNETIC FIELD PATTERN ASSOCIATED WITH GALACTIC OBJECT.

instability must be magnetic. Different models differ in detail. The model which I have been led to adopt⁸ is shown in Fig. 7. There is reason to believe that the magnetic field lines above a bipolar photospheric magnetic field region are partly closed and partly open. The open field lines will constitute a bipolar flux tube. A bipolar flux tube necessarily contains a surface of field reversal, this is, a sheet pinch. The coronal gas in the sheet pinch will have a higher pressure than normal coronal gas, and it is believed⁴² that this thin layer of gas of anomalously high density and temperature is what we recognize as a coronal streamer.⁴³

In this model, a solar flare represents the occurrence of the "tearing-mode resistive instability," analyzed by Furth, Killeen, Rosenbluth⁴⁴ and others, at the sheet pinch. The result of this occurrence is shown in Fig. 8. The instability permits the reconnection of magnetic field lines, allowing the field to move to a lower-energy configuration. The reconnected field lines are either coupled at both ends to the photosphere, or coupled at both ends to interplanetary space. The former are snapped back toward the photosphere, forming new closed field lines and giving rise to active loop prominences, whereas the latter move out into interplanetary space, carrying coronal gas with them and giving rise to a magnetic storm if this plasma cloud arrives at the earth. Strong electric fields develop during the resistive instability which can produce prompt acceleration of electrons to produce Type III radio bursts.³¹ The turbulent electromagnetic field which develops as a result of the instability can give rise to acceleration of both electrons and protons by the stochastic acceleration process.

One of the results of this model is that a "magnetic bag" containing high-energy plasma is catapulted away from the sun by the newly reconnected magnetic field lines. When this mass of plasma has been sufficiently accelerated, a shock wave will form in the surrounding corona, and it seems that this may be the shock wave which one needs to explain Type II radio bursts.³¹

Let us now consider what the result would be of a similar occurrence in the sheet pinch which we believe to form around a massive object con-



FIELD CONFIGURATION ABOVE CENTER
OF ACTIVITY WITH CORONAL STREAMER
(SHEAR NOT SHOWN)

FIG. 7. PROPOSED FIELD CONFIGURATION ASSOCIATED WITH CENTER OF ACTIVITY
AND CORONAL STREAMER.

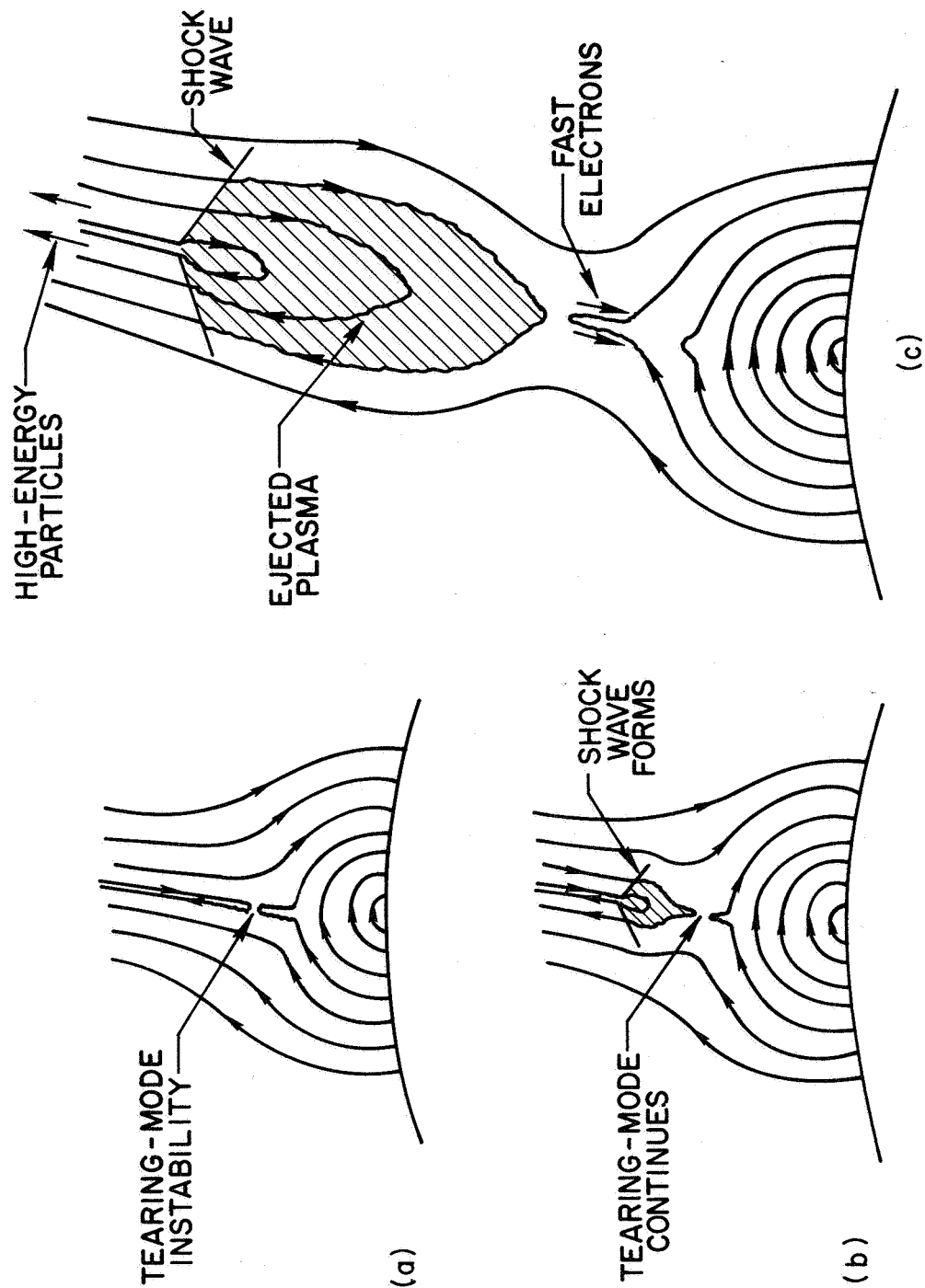


FIG. 8. PROPOSED FLARE MECHANISM ASSOCIATED WITH BIPOLAR FLUX TUBE.

densified from intergalactic gas. Once again, tearing of the field lines will lead to two volumes of high-energy plasma, one being catapulted toward the nucleus and the other catapulted away from the nucleus, as shown in Fig. 9. The former process might, when it occurs on a small scale, explain the light flashes from quasars. The second process would have the appearance of a jet, if the high-energy plasma were visible through synchrotron radiation. It is, therefore, tempting to identify the jet of the quasar 3C 273²⁵ and the galaxy M 87⁴⁵ with high-energy plasma clouds being ejected as the result of galactic flares. It is notable that the radio source 3C 273 forms at the tip of the optical jet, in analogy with a Type II radio burst which apparently forms at the tip of the plasma cloud ejected from the solar flare.

In order for the instability to have the form of a jet, rather than that of a ring, it is necessary either that the flare be confined to a certain small range of "longitude," or that the magnetic field in fact be highly distorted, looking more like the tail of the earth's magnetosphere (Fig. 10) than the model shown in Fig. 6. There are reasons for believing that the latter configuration could occur, but discussion of this possibility must be reserved for another occasion.

If the instability, which we may term a "galactic flare," is occurring in a certain range of longitude of the model shown in Fig. 6, it will develop as shown in Fig. 9, and this process will continue until the re-connected field lines, which are coupled to intergalactic space, relax as far as the Y-type neutral line. At this stage, the flare process will cease because all the available magnetic energy has been used up. The primary source of energy for the acceleration process is no longer available, but a large cloud of high-energy plasma is now situated at a bifurcation of the magnetic field. Unless the magnetic field configuration is in some way pathological, one would expect the cloud to divide into two parts, approximately equal in mass, and that half would go in one direction and the other half in the other direction. This leads naturally to the view that, some time later, the radio clouds would have the forms shown in Fig. 11, which closely resemble the typical double radio-cloud structure of radio galaxies and some quasars. However,

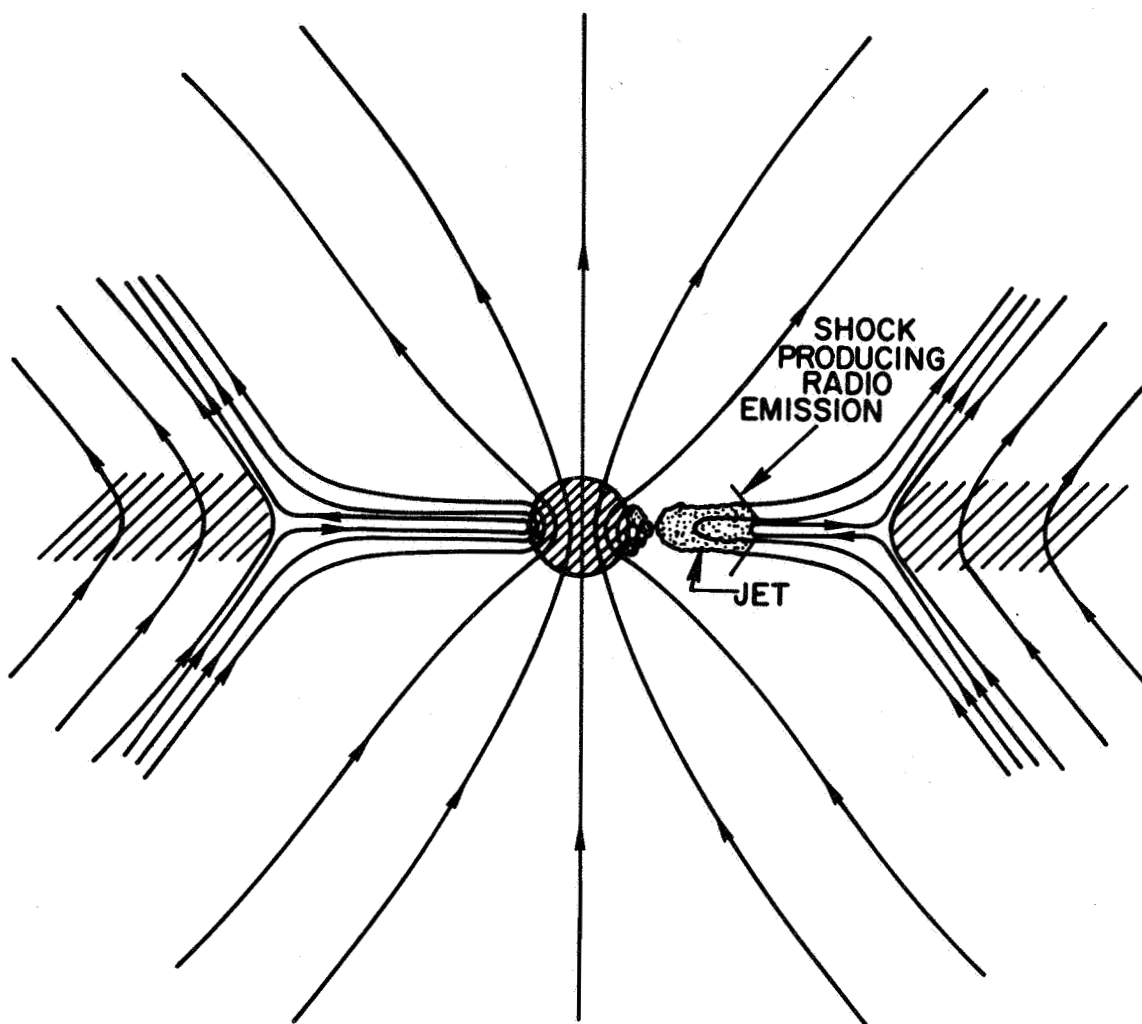


FIG. 9. PROPOSED FLARE ACTION IN FIELD CONFIGURATION OF FIG. 6.

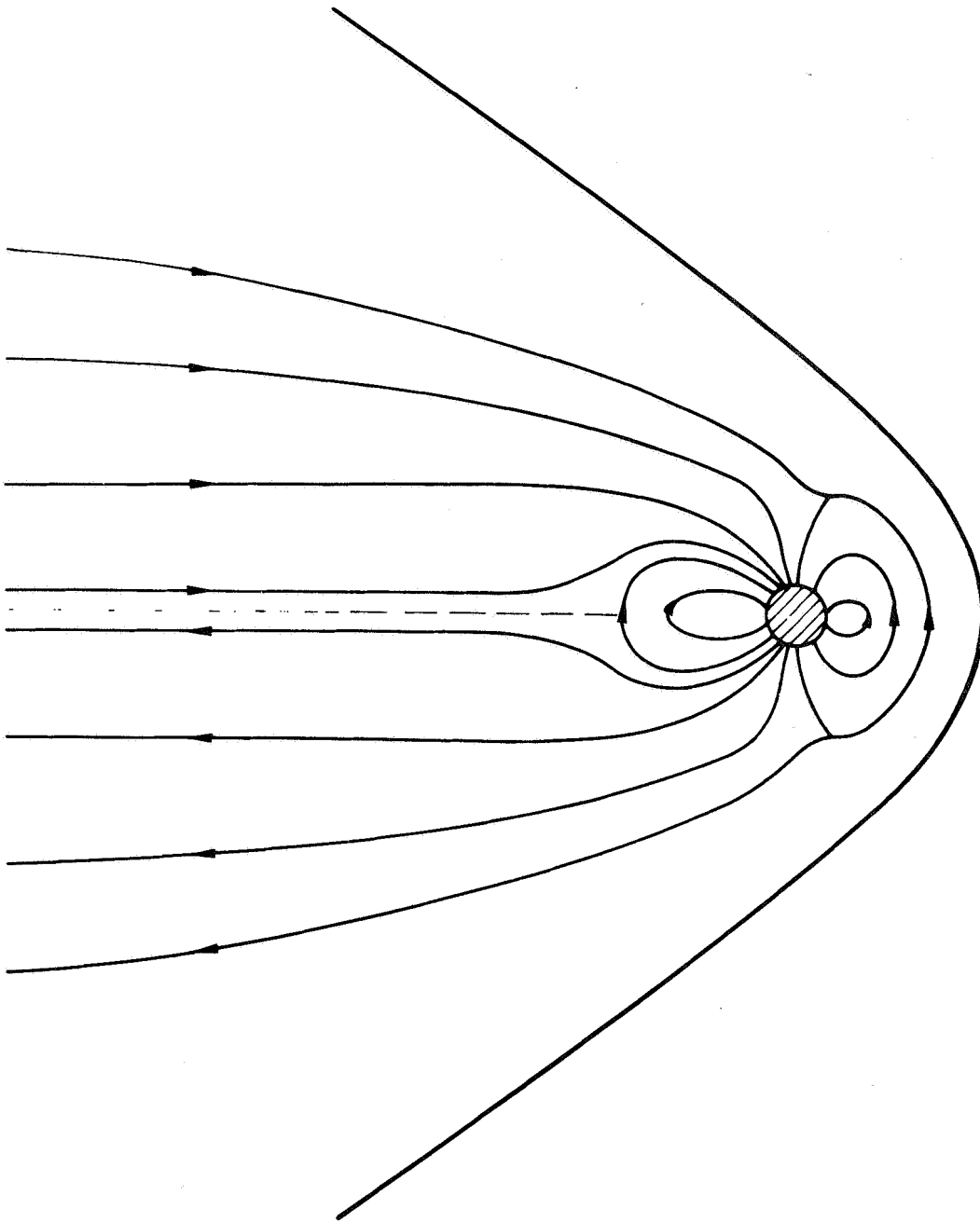


FIG. 10. ASYMMETRICAL MAGNETIC FIELD PATTERN, SIMILAR TO THAT OF THE EARTH'S MAGNETOSPHERE.

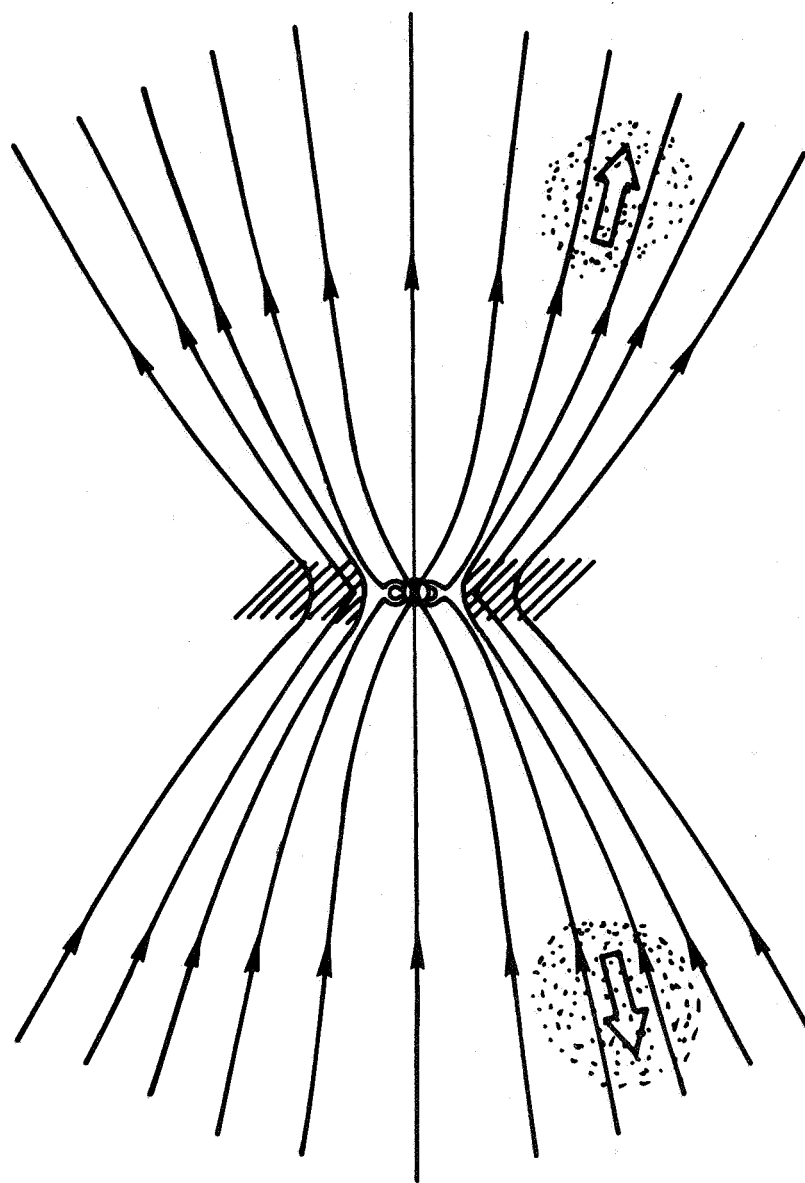


FIG. 11. DOUBLE RADIO CLOUD AS TERMINAL STAGE OF FLARE
ACTION OF FIG. 9.

the process is probably not quite as simple as this. Whether the plasma is guided by the magnetic field, or whether instead the magnetic field is distorted by the ejected plasma, depends upon the relative magnitudes of the velocity of the ejected plasma and the local Alfvén velocity. It seems more likely that the Alfvén speed will decrease with increasing radial distance, in which case a cloud which has been ejected as a single entity will remain such, so that the final state would be a single radio cloud traveling radially away from the nucleus.

The formation of a single radio cloud is unusual, and the occurrence of a jet is even more unusual. It seems, therefore, that the most frequent form of a galactic flare is due to a somewhat different topology of the magnetic field. In order to see what this form might be, we can consider the evolution of the field pattern shown in Fig. 6 due to continual accretion of matter. Matter which streams along the field lines coupled to the central nucleus will not affect the overall topology. However, matter which streams along the field lines feeding the "magnetic trap," will change the topology. As the mass of gas in the ring increases, the magnetic field will be squeezed toward the nucleus until the neutral sheet is replaced by an X-type neutral line, as shown in Fig. 12. If the build-up continues, a sheet pinch will reform, but this time in the form of a cylindrical sheet as shown in Fig. 13. It seems that this may be the typical magnetic field pattern in radio galaxies, the central object being the nucleus and the surrounding mass being the main body of the galaxy.

The above considerations offer an explanation of the division of the mass of the galaxy into a small central nucleus and an outer more dispersed mass. Over a certain group of field lines, and over a certain period of time, the influx velocity is less than the Alfvén velocity, so that the magnetic field can get rid of the angular momentum of the accreting gas and permit the formation of a compact mass: this is the nucleus. Gas which collects along field lines and over time intervals for which this condition is not satisfied will retain its angular momentum, leading to the formation of a dispersed mass of gas: this is the main body of the galaxy.

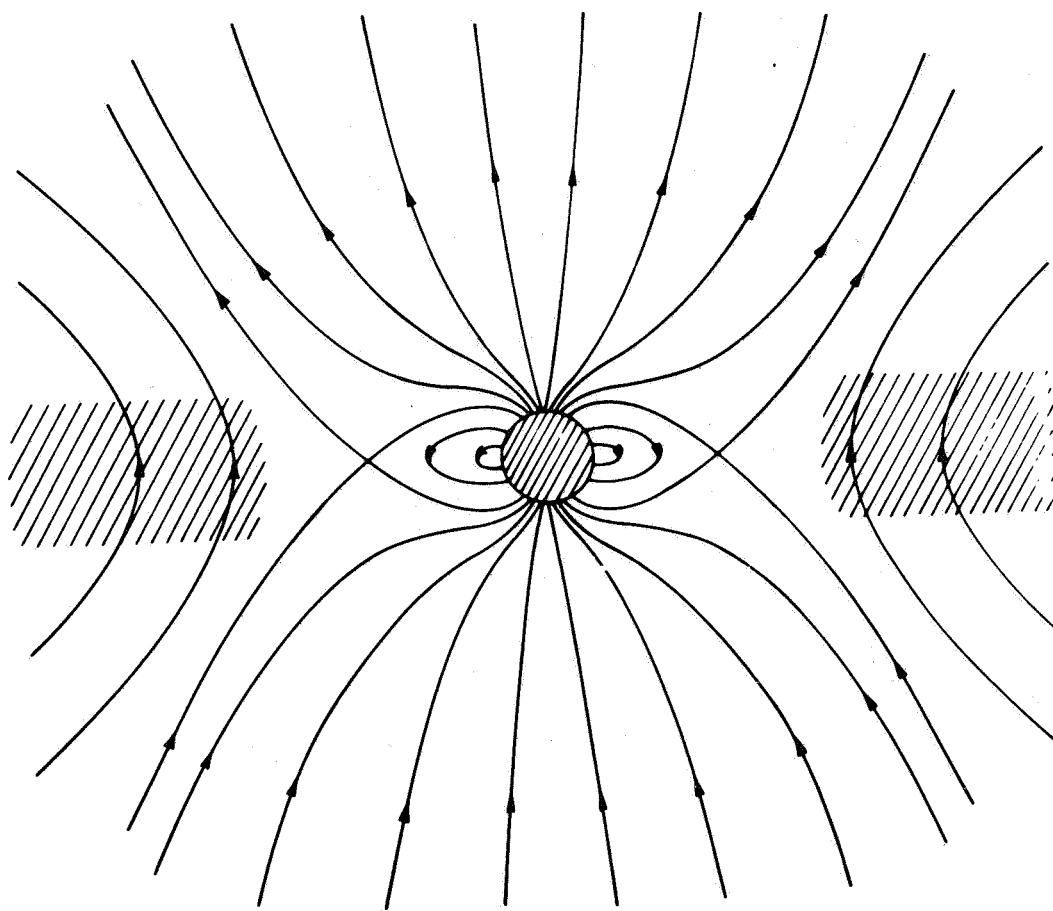


FIG. 12. DISTORTION OF MAGNETIC FIELD PATTERN OF FIG. 6 DUE TO ACCRETION IN RING TRAP.

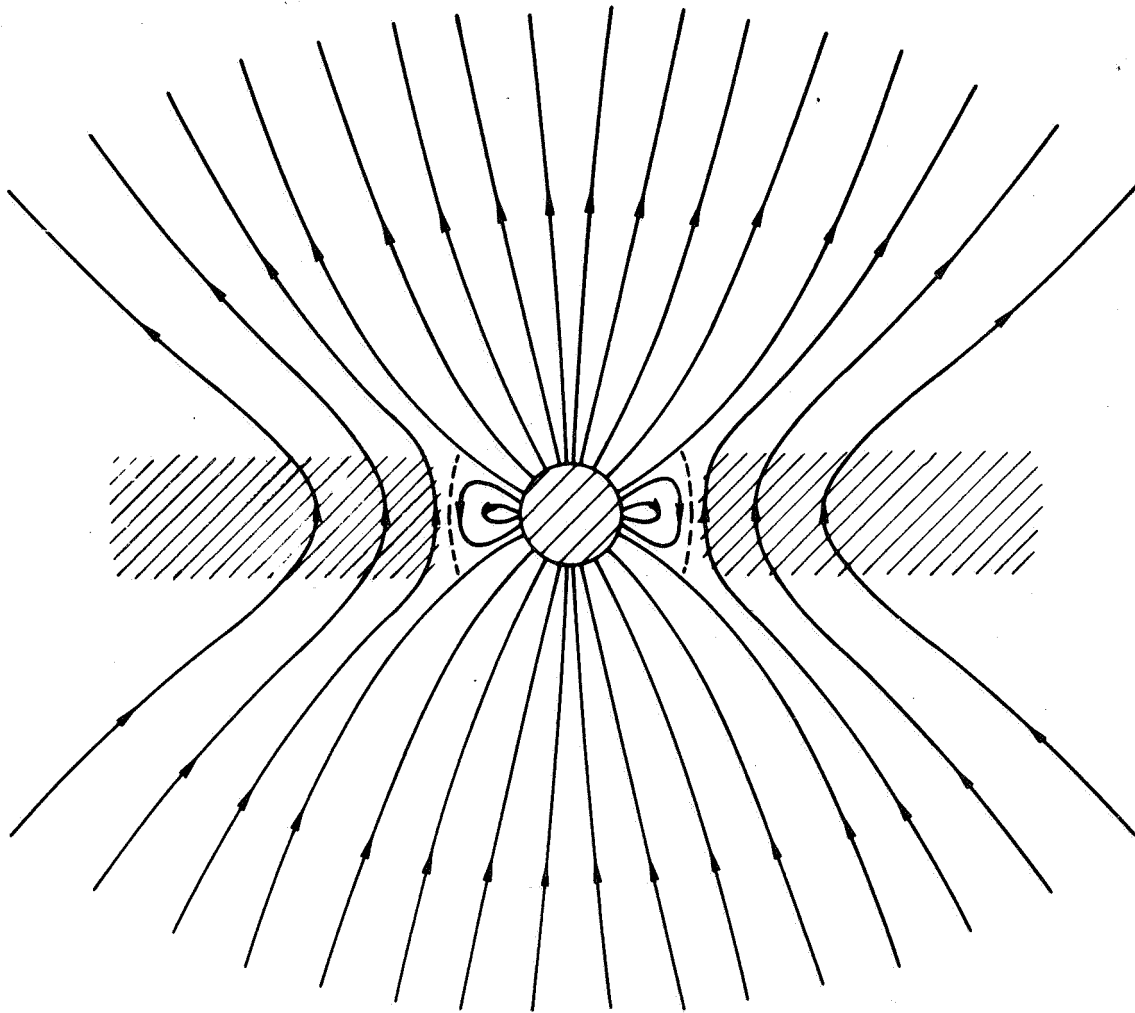


FIG. 13. FURTHER DISTORTION OF MAGNETIC FIELD PATTERN, LEADING TO FORMATION OF CYLINDRICAL SHEET PINCH.

It is clear that if a flare occurs on the sheet pinch depicted in Fig. 13, a double radio cloud is inevitable. If the flare occurs over only a small range of "longitude," the line joining the resulting clouds may not pass through the galaxy. If the flare occurs over the complete range of longitude, the resulting radio cloud should be symmetrically arranged with respect to the galaxy. Since the main body of a galaxy is typically much more massive than the nucleus, the flux connected to the nucleus will be much smaller than the flux connected to the main body. In consequence, the solid angle subtended by the field lines which connect to the nucleus should be fairly small. This offers an explanation of the fact that clouds remain fairly small in angular dimensions as they expand outward from a radio galaxy.

This is a brief sketch of a specific mechanism which might convert gravitational energy into radio energy. The development of this model has been strongly influenced by the apparent similarities between the electromagnetic phenomena in quasars and radio galaxies and similar phenomena which occur on the sun. However, this specific model was developed to meet certain general requirements, and in conclusion we may now review this general scheme for acceleration of particles on a galactic scale.

The general requirements are summarized in Fig. 14. Before an explosion can occur, there must be some form of stored energy. This energy is most likely derived from the gravitational energy of a dispersed mass of gas. Gravitational energy can be converted into other forms, such as kinetic and thermal, but the form most appropriate for electromagnetic purposes is conversion into magnetic energy.

An instability—representing the explosion—must convert stored energy into other forms of energy. If, as is here proposed, a large proportion of the stored energy is magnetic, the instability may be a plasma instability so that the explosion itself is an electromagnetic process. It may lead to some direct acceleration to very high energies. The instability may also give rise to the generation of streams of electrons and protons of moderate energy which may then lead to intense nonthermal radiation by a coherent mechanism such as a two-stream

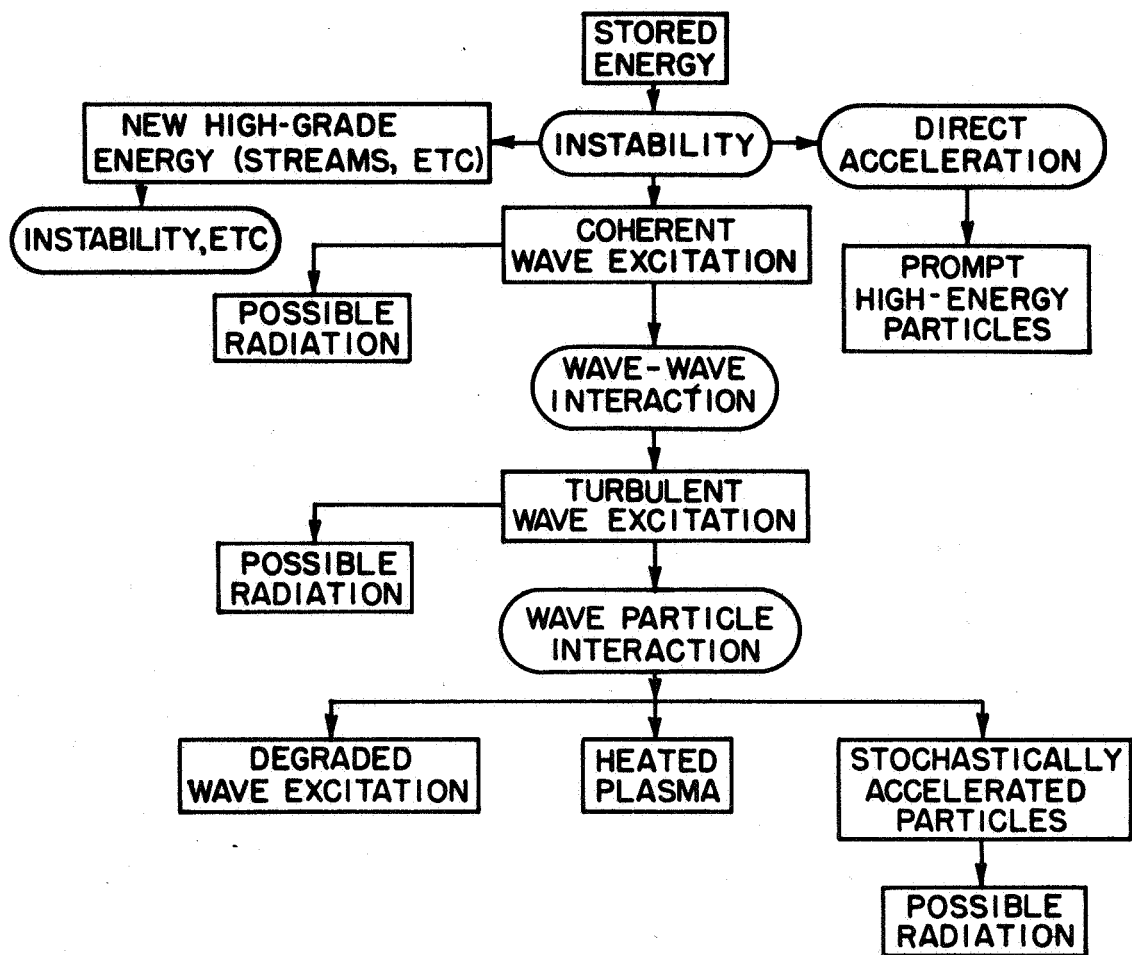


FIG. 14. POSSIBLE GENERAL SCHEME ASSOCIATED WITH GALACTIC EXPLOSIONS LEADING TO RADIO EMISSION.

instability.⁴⁶ This is a likely explanation of the intense radio bursts from quasars which were discussed earlier in this lecture.

An instability which converts energy by large-scale rearrangement of plasma and magnetic field will necessarily produce a very disturbed plasma. Soon after the instability has occurred, the state may be well described as one of large-amplitude excitation of a wide spectrum of waves, primarily magnetohydrodynamic in type. The evolution of this spectrum depends primarily on two processes: wave-wave interaction, and wave damping through wave-particle interaction. If the wave-wave interaction is the stronger effect, the wave spectrum should settle down to a "universal" spectrum, the form of which is determined by the wave-wave coupling mechanism.

The wave-particle interaction mechanism leads to stochastic acceleration of a certain group of particles and this in turn represents a damping process for the waves. Analysis of the behaviour of relativistic particles in random electromagnetic fields is being developed by Hall and Sturrock.²² This analysis enables one to identify several distinct acceleration mechanisms and it seems that discussion of the "selection rules" appropriate to each mechanism may enable one to identify the mechanism playing the dominant role in acceleration on a galactic scale.

If the plasma, magnetic field and high-energy particles form a closed system, the final state must be one of thermal equilibrium. However, the radiation and some of the high-energy particles can escape and the time scale for complete thermalization may be too great to be of interest. It seems more likely that a realistic "asymptotic state" will comprise several forms for the original stored energy: the thermal energy of hot plasma, a residual "noise" of the plasma, high-energy particles, and nonthermal radiation in the radio range and possible also in the optical part of the spectrum. The most important mechanism for conversion of the kinetic energy of high-energy particles to radiation is likely to be the synchrotron mechanism.

Figure 14 offers a possible chain of processes leading from stored energy, derived originally from gravitational energy, to the radio energy observed to be emitted from radio galaxies and quasars. There are a

number of formidable problems to be solved in developing this model. Although the linear theory of the tearing-mode instability has been developed, the nonlinear theory has not. Furthermore, the existing theory is non-relativistic, whereas it may be necessary to consider that the currents are associated with streams of relativistic particles. The theory of turbulence in neutral fluids has been developed,²⁰ but the theory of turbulence in plasmas¹⁸ is in an early stage. Both these problems must be analyzed in detail, and so also must the problem of determining the development of a mass of galactic gas which condenses from a region of space containing a primeval magnetic field.

The problem of acceleration by stochastic electromagnetic fields has now been analyzed in some detail, and the results will be published in the near future.²²

Although extensive calculations will be essential to confirm the model now proposed in outline form, the qualitative and gross quantitative agreements between this model and the high-energy phenomena of quasars and radio galaxies seem to be highly encouraging.

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