DOUBLE RADIO SOURCES AND THE NEW APPROACH TO COSMICAL PLASMA PHYSICS

H. ALFVÉN

Dept. of Plasma Physics, Royal Institute of Technology, Stockholm, Sweden

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Abstract. The methodology of cosmic plasma physics is discussed. It is very hazardous to try to describe plasma phenomena by theories which have not been carefully tested experimentally. One present approach is to rely on laboratory measurements and *in situ* measurements in the magnetosphere and heliosphere, and to approach galactic phenomena by scaling up the well-known phenomena to galactic dimensions. A summary is given of laboratory investigations of electric double layers, a phenomenon which is known to be very important in laboratory discharges. A summary is also given of the *in situ* measurements in the magnetosphere by which the importance of electric double layers in the Earth's surrounding is established. The scaling laws between laboratory and magnetospheric double layers are studied. The successful scaling between laboratory and magnetospheric phenomena encourages an extrapolation to heliospheric phenomena. A further extrapolation to galactic phenomena leads to a theory of double radio sources.

In analogy with the Sun which, acting as a homopolar inductor, energizes the heliospheric current system, a rotating magnetized galaxy should produce a similar current system. From analogy with laboratory and magnetospheric current systems it is argued that the galactic current might produce double layers where a large energy dissipation takes place. This leads to a theory of the double radio sources which, within the necessary wide limits of uncertainty, is quantitatively reconcilable with observations.

1. Introduction

Double radio sources constitute one of the most puzzling problems in astrophysics. Typically such sources emit 10^{42} erg s^{-1}, in extreme cases even one or two (or even three) orders of magnitude more. Usually a galaxy is situated almost exactly half way between the radio sources.

Most theories of these objects have followed essentially two different lines. Some scientists have postulated that there are stellar objects in the centre of the radio stars which deliver the energy, but none has been found so far. Others have postulated that the galaxy in the centre has emitted two jets in the opposite directions, which in some way have been kept together during their long travel. Both the emission mechanisms and the focussing mechanisms suggested so far seem to be highly speculative and there is no serious attempt to outline where the energy ultimately comes from. Moreover, the plasma formalism on which these theories are based is in general of a type which is found to be invalid in all those regions of space (magnetosphere and parts of the heliosphere) which have been explored through *in situ* measurements by means of spacecraft.

According to Hargrave and Ryle (1974) none of these theories is reconcilable with

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observation. These authors conclude that energy must be continuously transported to the radio sources from the central galaxy.

2. General Approach to Cosmical Plasma Physics

Theoretical plasma astrophysics is usually based on a formalism which broke down in the laboratory about 20 years ago (the 'thermonuclear crisis'). Its application to the magnetosphere has proved to be invalid during the last five or ten years (see Alfvén, 1968, 1975, 1976, 1977 and Alfvén and Arrhenius, 1976). In this 'pseudoplasma' formalism one neglects a number of important plasma phenomena (e.g. electrostatic double layers, current sheaths, pinch effect, critical velocity) which now are generally recognized to be of decisive importance (see Alfvén, 1968; Fälthammar, 1974, 1977; Block and Fälthammar, 1976; Block, 1972a, b, 1975, 1977; Sherman, 1973; Danielsson, 1973). Difficulties are also due to the fact that a plasma is often so complicated that it cannot be understood without very careful diagnostics, which are impossible to make without *in situ* measurements.

It seems that a new approach is needed and should be based on the recognition of the fact that the plasma has general patterns of behaviour which, in important respects, are the same in the laboratory and in the ionosphere–magnetosphere–heliosphere. We may expect that the general pattern is also the same in the more distant regions of space which still are inaccessible to *in situ* measurements.

This approach means that it may be possible to extrapolate from one situation to another. Methods to translate laboratory measurements to magnetospheric conditions are now very important in clarifying the conditions in the magnetosphere (see Alfvén, 1968; Fälthammar, 1974; Block, 1976). One can also with some confidence extrapolate from one geometrical situation to another and also to a plasma which has a different density, temperature or magnetization.

In the following we shall use this approach and show that the double radio stars may be analogous to certain processes which are well known in the laboratory. These phenomena have been extrapolated successfully to the magnetosphere, and, as a third step, also to the heliosphere. We may consider the double radio sources to be the fourth link in this series of extrapolations.

3. First Case. Electric Double Layers in Laboratory Discharges

An electric current I in a discharge tube often produces electrostatic double layers (see Torvén and Babić, 1975, 1976, 1977). This phenomenon has been known for a century. It is often very complicated but the basic mechanism is fairly well understood (Block, 1975, 1977). It is a purely electrostatic phenomenon and can be produced even in the absence of any appreciable magnetic field. Over a distance of the order of 10–100 Debye lengths there is a voltage drop ΔV produced by a thin layer of positive charge close to another layer of negative charge. A power $P = I\,\Delta V$ is dissipated, primarily in the form of accelerated charged particles.

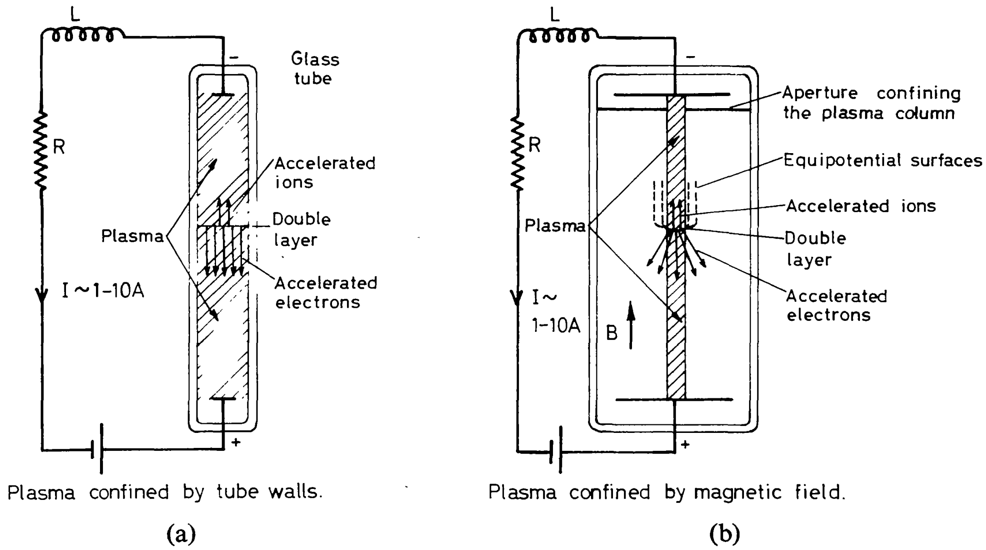


Fig. 1. Electrostatic double layers in laboratory discharges (Torvén and Babić, 1975, 1977).

A double layer is often produced at a point where the diameter of the discharge tube changes, but it is also possible to set up such a double layer at any point of a uniform glass tube in which the plasma is confined (see Figure 1(a)). The energy release in the double layer may be so large that at the point where it is set up the glass tube glows and even implodes. The double layer usually oscillates and emits noise with a very broad frequency spectrum. The power P is supplied by a voltage source in the circuit which may be located at any distance. The energy is transferred to the double layer by the electric circuit. The behaviour of the double layer depends not only on the plasma parameters near it but also on *the resistance and inductance in the whole circuit*, as is clearly demonstrated by Torvén. For example, if a large inductance is introduced, the layer may explode and completely disrupt the current. In this case most of the magnetic energy in the circuit is released at the layer in a very short time (often in a few microseconds).

The study of double layers shows in a drastic way how inadequate much of the usual plasma formalism is. What is probably a very important mechanism of energy transfer is usually neglected.

If a longitudinal magnetic field is applied, this may partially confine the plasma to a cylinder at such a distance from the walls that their influence becomes negligible (see Figure 1(b)). Outside the plasma column marked in the figure the degree of ionization is much lower, although not negligible. Also in this case double layers can be produced. This shows that in the above experiment the walls are not essential (although in certain respects they influence the plasma behavior). If the magnetic field is so strong that the electron Larmor radius is small compared to the distance to the walls, the equipotential surfaces of the double layer are continued as cylinders enclosing the *cathode* side of the plasma column. Outside the equipotential cylinders there is no appreciable electric field (under the condition that the ionization in the surroundings is above a certain rather low value). Hence the equipotential surfaces have the same shape as around a cable immersed in a conducting medium. This means that in certain respects *the plasma column is similar to a metal wire surrounded by an insulator*. This state is difficult to describe by the ordinary plasma formalism, especially as this must include as 'boundary conditions' the inductance and resistance of the circuit. In fact in many cases the ordinary circuit theory is more useful: we may represent the plasma by an insulated metal wire and the double layer by a non-linear circuit element.

4. Second Case. The Auroral Circuit

Recent magnetospheric–ionospheric research has demonstrated that at the dawn side of the auroral zone there are currents flowing into the auroral zone at high latitudes and leaving the zone at somewhat lower latitudes (Zmuda and Armstrong, 1974; Boström, 1974, 1975a, b). (At the evening side the currents have reversed direction.) The currents flow in sheets along the magnetic field lines (Birkeland currents). The circuit is closed in the upper ionosphere and in the plasma near the equatorial plane. Seen from a non-rotating coordinate system the e.m.f.

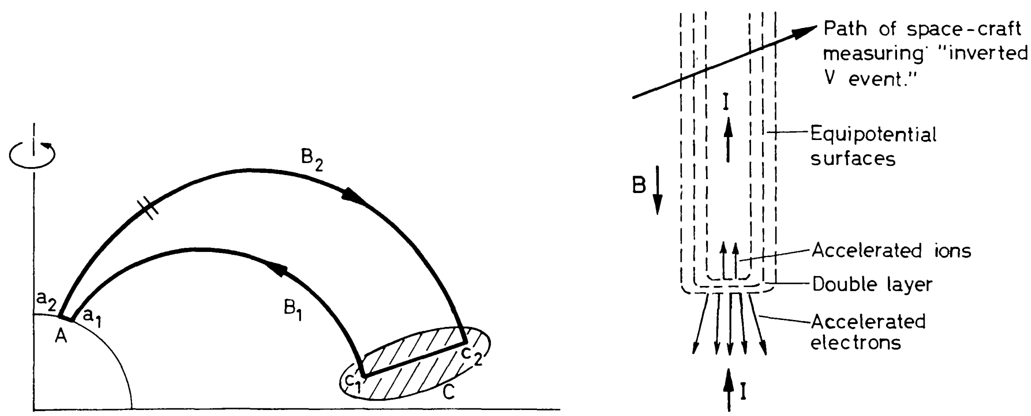
$$V = \int (\mathbf{v} \times \mathbf{B}) \cdot \mathrm{d}\mathbf{s} \tag{1}$$

is essentially due to the polarization of the plasma in the equatorial plane which drifts in the Sunward direction with velocity $\mathbf{v}$ and has a magnetization $\mathbf{B}$. Also, the ionosphere gives a contribution to the integral, but this is usually smaller.

In the regions where the current flows upwards from the auroral zone, one or more electrostatic double layers are often produced at a height of about 5000 km (Shawhan *et al.*, 1977). The complicated phenomena associated with this are far from fully understood, but a recent theory by Lennartsson (1976, 1977a, b) seems to explain at least the basic mechanism. (See Figure 2(a).)

Above the double layer (or layers) the equipotential lines seem to form cylinders around the current carrying flux tube, similar to what happens in the laboratory. A spacecraft passing this configuration registers an 'inverted V event' (Gurnett, 1972). Below the double layer there is a beam of high energy electrons, accelerated at least in part in the double layer. They are often almost monochromatic and their pitch angles are often small. Most of their energy is dissipated in the ionosphere where they produce aurora. (See Figure 2(b).)

It is evident that in essential respect this magnetospheric phenomenon is similar to the laboratory phenomenon discussed in §3. In an electrostatic double layer (or perhaps in a series of such layers) charged particles are accelerated. The power $P = I\,\Delta V$ which is required for this is taken from an energy source far away. In fact, the primary source of energy in the magnetospheric circuit is the kinetic energy of the sunward convection of plasma in the equatorial plane. (We shall not discuss here the mechanism through which this energy is replenished; ultimately it comes from the solar wind.)



(a) (b)

Fig. 2. Electrostatic double layers in the magnetosphere. Compared to laboratory phenomena the scale is 10^9 times larger. (a) The circuit is constructed from measurements by Zmuda and Armstrong (1974). (b) Details of the double layer, Gurnett and Frank (1972, 1973) and Block (1975).

In the laboratory the energy is supplied from the kinetic energy of the rotor in the electric generator which serves as the energy source. In both cases energy is transmitted to the double layer over a large distance. The energy is transferred through the electric circuit. As in all circuits this can be envisaged as a Poynting vector energy transfer. The electric current I which transfers the energy to the layer is carried by thermal electrons which have a much lower energy before they enter the layer than after they have passed through it. Of course, the energy release in the double layer has nothing to do with 'magnetic merging' (cf. Heikkila, 1977). In the magnetotail a current is flowing in the equatorial plane. According to Boström (1975a) this current may give rise to double layers, which sometimes explode. Although this phenomenon is not explored as much in detail as the auroral current system, the function of such double layers may be the basic phenomenon in magnetic substorms.

5. Third Case. Heliospheric Current System

Of the heliospheric current system only the part of the circuit which is located in the equatorial plane has been explored by *in situ* measurements (Figure 3). These show that the radial component of the current is about 3×10^8 A. From Kirkhoff's law we conclude that this current flowing towards the Sun must be closed by currents leaving the Sun, which means that there must be high latitude outwards currents which, in case of symmetry, are 1.5×10^9 A in each hemisphere. How close to the axis these currents flow is unknown, but it is likely that the 'polar plumes' in the solar corona mark their foot print (see further Alfvén, 1977).

If we compare the heliospheric and the auroral current systems we find that they

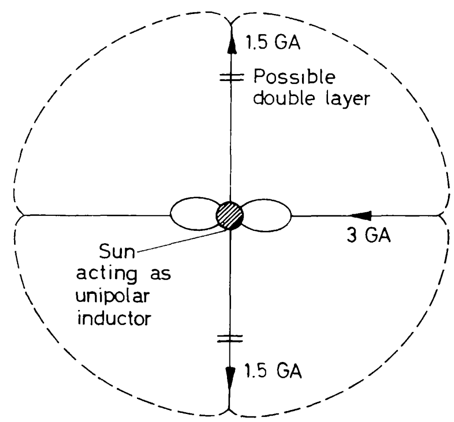


Fig. 3. Heliographic current system. The current in the equatorial plane is measured by spacecraft. The axial currents are derived from Kirkhoff's law. The prediction of double layers at the axis are based on analogy with the auroral circuit.

are similar in essential respects. In both cases the e.m.f. is due to the integral in Equation (1) being different from zero. However, there are a number of modifications:

1. The main e.m.f. is produced by the Sun, which acts as a unipolar inductor. The plasma motion in the equatorial plane is due to the solar wind which is essentially radial with the result that the integral taken over this part of the circuit is zero. The current system is azimuthally symmetric. (Concerning the 'sector structure', see Alfvén, 1977.)

2. Because the current is large enough to modify the dipole field considerably, and because of the solar wind, the equatorial current extends over a very large region and is spiralled. Further, the poleward branch of the Birkeland currents is moved close to the axis (how close is not known). The circuit is closed at a very large distance – in any case, outside the region yet explored by spacecraft.

A very important question is whether in the heliospheric circuit there is an analogy to the double layers in the auroral circuit. By analogy with the magnetosphere we may expect such layers high above the surface of the Sun in each of the polar regions. Because the solar circuit is azimuthally symmetric (as indicated by the measurements in the equatorial plane), we should expect the double layers to be symmetric with reference to the axis of the Sun, most probably located on the axis.

Arguments of this kind have led to the prediction that there should be two double layers (or set of double layers) on the solar axis, one in each hemisphere. Such layers should, in principle, be detectable through the high frequency noise they emit or through the charged particles which they accelerate. However, there are two reasons why we cannot claim that the prediction is very reliable. First, the general theory of the formation of such layers in space is not yet worked out in detail. Second, we are not well acquainted with the plasma properties in these regions because no *in situ* measurements have yet been made there. It is not yet possible to decide whether the layers should be just above the solar surface or very high up.

It seems that the Jovian magnetosphere is similar to the heliosphere, but at the moment there are insufficient measurements for definite conclusions. Also, the current in the equatorial plane of the Sun may produce double layers, in analogy with the current in the magnetotail.

6. Fourth Case. The Radio Double Source

If, in the heliospheric circuit, we replace the rotating magnetized Sun by a galaxy, which also is magnetized and rotating, we should expect a similar current system, only magnified linearly by about nine orders of magnitude. This seems to be a very large extrapolation, but in reality the successful extrapolation from the laboratory to the magnetosphere is by almost the same ratio.

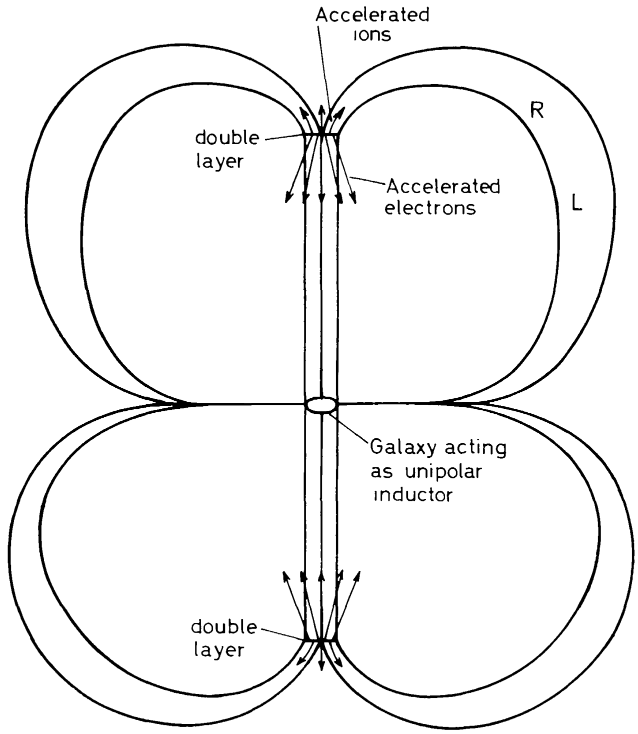
The e.m.f. is given by the integral in Equation (1) taken from the galactic centre out to a distance where the current leaves the galaxy, which may be the outer edge. Inside the galaxy the current may flow in the plane of symmetry similar to the current sheet in the equatorial plane of the Sun, but whether the intragalactic picture is correct or not is not really important to our discussion.

The e.m.f. which derives from the galactic rotation is applied to two circuits in parallel, one to the 'north' and one to the 'south'. As galaxies, in general, are highly north–south symmetric it is reasonable that the two circuits are very similar. Hence we expect a high degree of symmetry in the current system.

In the magnetosphere the current flowing out from the ionosphere produces double layers at some distance from the Earth (cf. Shawhan *et al.*, 1977 and Lennartsson, 1977a). Because of the similarity of the plasma configuration we expect *double layers at the axis of a galaxy*, and a large release of energy in them. It is suggested that *the occurrence of such double layers is the basic phenomenon producting the double radio sources* (Figure 4(a)). This agrees with Hargrave and Ryle's (1974) conclusion that energy must be continuously supplied to the radio sources from the central galaxy.

In the galactic circuit the e.m.f. is produced by the rotating magnetized galaxy, which implies that the energy is drained from the galactic rotation. By the same mechanism as in the auroral circuit, it is transferred to the double layers where the power $P = I\,\Delta V$ is released. In one or probably a large number of adjacent double layers at each side of the galaxy an acceleration of charged particles takes place. From the magnetosphere we know that layers are produced when the current flows outwards. (Whether double layers can be formed when the current flows inwards is still an open question.) If the same is true in the galactic case, there is a flow of thermal electrons to the layer from the outside, and when passing the series of double layers these get accelerated to very high energies. Hence, *a beam of very high energy electrons is emitted from the double layer along the axis towards the central galaxy*. The process we have described is just the same as that which produces auroral electrons, only scaled up enormously both in size and energy.

In analogy with the current in the magnetotail, the current in the equatorial plane



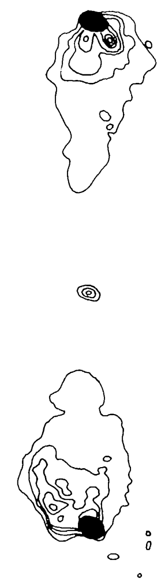


Fig. 4. Galactic circuit. (a) The heliographic circuit is scaled up by a factor 10^9 and the Sun is replaced by a galaxy. (b) Observed radio emission attributed to synchrotron emission by electrons accelerated in the double layer. The galaxy delivering the energy is located almost exactly between the radio sources.

of a galaxy may also produce double layers, which may be associated with large release of energy.

7. Comparison with Observations

Figure 4(b) shows the radio astronomy picture of a double radio source. It is essential in our model that the e.m.f. of the galaxy has such a direction that the axial currents flow outwards. The double layer they produce should be located at the outer edges of the strong radio sources. When electrons conducting the currents outside the double layer reach the double layer, they are accelerated to very high energies. Similarly, ions reaching the double layer on their outward motion from the central galaxy, will be accelerated outwards when passing the double layers. The strong axial current produces a magnetic field, which pinches the plasma, confining it to a cylinder close to the axis.

Although the electrons are primarily accelerated mainly in the direction of the magnetic field, they will be scattered by magnetic inhomogeneities and will spiral in such a way that they emit synchrotron radiation. With increasing distance from the double layer they will spread, and their energy and hence their synchrotron emission will decrease. This is in agreement with the observational picture. It is possible that some of them will reach the central galaxy, and produce radio emission there. It is also possible that the observed radio emission from the central galaxy is due to some other effect produced by the current. There are several possible mechanisms. We shall not discuss the phenomena in the central galaxy in this paper.

The ions passing the double layer in the outward direction will be accelerated to the same energy as the electrons. Because of their larger rest mass they will not emit much synchrotron radiation, but there are a number of other mechanisms by which they may produce the observed radio emission from the regions further away from the central galaxy.

It should be stressed again that, just as in the magnetosphere and in the laboratory, *the energy released in the double layer is transferred to it by electric currents which essentially consist of relatively low energy particles.* There is no need for a beam of high energy particles to be shot out from the central galaxy (and still less for some mysterious 'plasmons'). On the contrary, the central galaxy may be bombarded by high energy electrons which have obtained their energy from the double layer.

Like most field aligned currents in cosmical plasmas, the currents flowing from the central galaxy to the double layers are likely to be pinched. This means that they consist of one or more filaments. The magnetic field is of the order $\mathbf{B} = I/r$, where r is the radius of the filament or the bunch of filaments. In circuit theory the magnetic energy in the circuit is described as being due to an inductance L, such that

$$\tfrac{1}{2}LI^2 = \int \frac{\mathbf{B}^2}{8\pi}\,\mathrm{d}\tau,$$

where I is the current. The integral should be taken over the whole region where I produces a magnetic field. The circuit also contains a resistor R.

We do not yet know with certainty what decides the height of the auroral double layers. Presumably the position is given by the electric field produced by the mirroring of charged particles which are carrying the current (Lennartsson, 1977a). Hence, it is difficult to decide what determines the distance from the central galaxy to the double layers. It seems likely that the currents from the central galaxy to the double layers are pinched, but outside the double layers the current lines as well as the magnetic field lines diverge, so that the currents spread laterally on their way to 'infinity' or towards the outer edge of the central galaxy which they eventually must reach in order to close the circuit.

In the same way that the Sun's rotational axis is not exactly perpendicular to the ecliptic plane, the axis through the radio sources need not necessarily be perpendicular to the galactic plane. Furthermore, not only the axial currents but also the current in the equatorial plane may set up double layers which release energy. Hence radio sources may be produced both at the axis, or not very far from it, and in the equatorial plane. Gibson (1975) has investigated statistically the location of double radio sources with respect to the rotational axis of galaxies. He finds that the assumption of a random distribution agrees somewhat better with observations than a preference close to the axis or close to the plane of symmetry. As he does not distinguish between the two cases we have discussed, there seems to be no conflict between his observational results and our model.

It is difficult to predict theoretically whether the radio sources should be at a time constant distance from the central galaxy or whether they should move outwards (be 'shot out' from the galaxy). In principle, they may even move towards the galaxy. Observations seem not to give any indication of an outward motion. It is possible that the distance is a function of the current. If two or more pairs of radio sources are found at different distances from the central galaxy this does not indicate that there has been a 'series of explosions' in the galaxy. A current in a plasma can very well produce consecutive double layers in several regions.

8. Discussion

Very little can be understood about a complicated phenomenon unless we first of all determine how it is energized. Contrary to earlier theories, which usually have postulated an unknown mechanism for the transfer of energy, our approach centers on this.

Furthermore, contrary to earlier attempts to understand the double radio sources, our approach includes *no ad hoc assumptions*. The only assumption we make – if it should be called so – is that a plasma has the same general properties in the laboratory, the magnetosphere, heliosphere, and a galaxy. More specifically, we have found that the same circuit can describe essential properties of a plasma in the first three cases, and from this we conclude that the same circuit might also be applicable in the galactic case.

The circuit consists of an e.m.f., a resistance, an inductance, and electrostatic double layers. The difference between the four cases it is applied to, is essentially geometric. The energy source is the rotor of an electric generator or a rotating star or a rotating galaxy acting as a unipolar inductor in the cosmic cases. Only in the case of the magnetosphere is it somewhat different, viz. the translational motion of a plasma. In detail there are, of course, a number of differences. The magnetospheric current system is often highly asymmetric in the north–south direction because of the summer–winter asymmetry in ionospheric conductivity. Contrary to this the heliosphere system may, on average, be symmetric with reference to the Sun's magnetic equatorial plane, but is moving up and down with considerable amplitude. In the galactic case there seems often but not always to be a symmetry with reference to a straight line through the central galaxy, but the line does not in general coincide with the axis of rotation.

9. Quantitative Considerations

After this qualitative analysis it is essential to check whether our model is acceptable from a quantitative point of view. Unfortunately, what is known about the cosmic conditions is very uncertain so our calculations may easily be in error by one order of magnitude – perhaps in some cases even more. The current in the circuit is driven by an e.m.f. between the centre and periphery of the galaxy: i.e.,

$$V_{\text{gal}} = \int (\mathbf{v} \times \mathbf{B}_{\text{gal}})\, \mathrm{d}r,$$

where $\mathbf{v}$ is the velocity of galactic rotation, $\mathbf{B}_{\text{gal}}$ is the magnetic field component perpendicular to the galactic plane and r the radius. We know very little about these quantities for the central galaxies associated with double radio sources. If we take order of magnitude values for our own galaxy: $\mathbf{v} = 10^8$ cm s^{-1}, $\mathbf{B} = 10^{-6}$ gauss, $r = 3 \times 10^{22}$ cm, we obtain $V_{\text{gal}} = 3 \times 10^{24}$ emu $= 3 \times 10^{16}$ V, a value which easily may be wrong by one or more orders. In case only the galactic nucleus plays an important role we should put $r = 3 \times 10^{21}$ cm but probably increase $\mathbf{B}$ by one order of magnitude, which gives the same value for V.

The circuit equation is

$$V_{\text{gal}} - \Delta V = RI + L\frac{\mathrm{d}I}{\mathrm{d}t},$$

where ΔV is the potential over the double layer, and R and L the resistance and inductance of the circuit. If R is negligible (as is often the case in cosmic situations) the current grows as long as $V_{\text{gal}} > \Delta V$. If $\Delta V = V_{\text{gal}}$ the current is constant. An energy dissipation of a typical observed value of 10^{41} erg s^{-1} $= 10^{34}$ W requires a current of $I = 3 \times 10^{16}$ emu $= 3 \times 10^{17}$ A. This current may be distributed in a number of parallel filaments, each producing a number of double layers.

If the distance between the radio sources is 10^{24} cm, the inductance of the circuit may be of the order $L = 10^{24}$ cm $= 10^{15}$ H and the magnetic energy $W_{\text{mag}} = \frac{1}{2}LI^2$ of the order 10^{57} erg $= 10^{50}$ J. As the kinetic energy of a galaxy with mass 10^{44} g and velocity 10^8 cm is of the order 10^{60} erg $= 10^{53}$ J, the required magnetic energy is only a small fraction of the galactic kinetic energy. However, it should be observed that primarily only the kinetic energy of the interstellar medium is available because it is difficult to brake the motion of stars.

If suddenly V_{gal} becomes zero, the current will continue to flow but it will decrease with the time constant $T_c = LI/\Delta V = 10^{16}$ s $= 3 \times 10^8$ yr.

None of these values is irreconcilable with what we know about galaxies and double radio stars. Hence there seems to be no obvious quantitative objections to our model. On the other hand, our real knowledge of the conditions is so uncertain that we cannot speak of a quantitative confirmation.

Under certain conditions double layers are known to 'explode'. The voltage drop increases very rapidly, with the result that the dissipated power rapidly increases by several orders of magnitude. Under laboratory conditions ΔV may go up from 10 volts to 100 000 volts in a few microseconds. Cosmical examples of similar explosions are solar flares (see Carlqvist, 1969), magnetic substorms (see Boström, 1975a, b) and the 'folding umbrella' phenomenon in cometary tails (Ip and Mendis, 1976). Hence it would not be surprising if a radio source which normally is characterized by the above values dissipates several orders of magnitude more energy during a limited period of time. This period may be much longer than the period during which the objects have been observed. The energy which is dissipated in the radio sources is primarily taken from the inductive energy of the circuit, and is essentially independent of the conditions in the galaxy during the last period T_c.

The enormous energy release in the radio sources makes it likely that the energy transfer to them has been essential for the formation or evolution of the galaxy. The tapping of rotational energy means that the interstellar medium falls down towards the nucleus. Because of the uncertainty in our calculations, T_c may perhaps be the age of the galaxy. The origin of the inductive energy is the kinetic energy of the galaxy and this may have been tapped when the galaxy was formed.

10. Production of Cosmic Rays

The ΔV and I values we have found bring us up in the range of the most energetic cosmic radiation. In fact, the double layers should emit ions with an energy

$$W = Ze\,\Delta V,$$

where Z is the charge of the ion. With $\Delta V = 3 \times 10^{16}$ V, an ion with $Z = 30$ gets an energy of 10^{18} eV.

Also a betatron acceleration in a pinching current may give energies in the same range. In fact, if a current I produces a magnetic field $\mathbf{B} \approx I/r$, this field can contain and accelerate particles with a rigidity $\mathbf{B}\varrho = I$ and the betatron acceleration may bring up the particles to an energy $W = ZeI$, which with $I = 3 \times 10^{17}$ A $= 3 \times 10^{16}$ emu and $Z = 30$ means 3×10^{20} eV. The total energy delivered as very high energy cosmic rays should be an appreciable fraction of the energy of the synchrotron radiation from the radio source.

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