# PART V

# ELECTROMAGNETIC STATE IN INTERPLANETARY SPACE

## A. THEORIES OF MAGNETIC STORMS

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# A. THEORIES OF MAGNETIC STORMS

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# THE PRESENT STATE OF THE CORPUSCULAR THEORY OF MAGNETIC STORMS

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## ABSTRACT

The evidence in favour of a corpuscular theory of magnetic storms is briefly reviewed and reasons given for believing that the stream must be neutral but ionized and carry no appreciable current. It is shown that under suitable conditions the stream is able to pass freely through a solar magnetic field; the stream may also be able to carry away with it a part of this field. However, because of geometrical broadening of the stream during its passage from the sun to the earth, the magnetic field imprisoned in the gas may be wellnigh unobservable near the earth.

The nature, composition and dimensions of the stream near the earth are discussed and it is concluded that on arrival the stream will present very nearly a plane surface to the earth if undistorted by the magnetic field.

Because of its large dimensions, the stream will behave as if it were perfectly conducting. During its advance in the earth's magnetic field the currents induced in the stream will therefore be practically confined to the surface. The action of the magnetic field on this current is to retard the surface of the stream which being highly distortible will become hollowed out. Since the stream surface is impervious to the interpenetration of the magnetic tubes of force, these will be compressed in the hollow space. The intensity of the magnetic field is thereby increased and this increase is identified with the beginning of the first phase of a magnetic storm. This increase will be sudden, as observed, owing to the rapid approach of the stream to the earth.

The distortion of the stream surface is discussed and it is pointed out that two horns will develop on the surface, one north and the other south of the geomagnetic equator. Matter pouring through these two horns will find its way to the polar regions.

The main phase of a magnetic storm seems most simply explained as due to a westward ring-current flowing round the earth in its equatorial plane. Under suitable conditions such a ring-current would be stable if once set up. The mode of formation of the ring is, however, largely conjectural. The possibility that the main phase may be of atmospheric origin is also briefly considered. It is shown that matter passing through the two horns to the polar regions could supply the energy necessary for the setting up of the field during the main phase. The magnetic evidence in favour of such a hypothesis, however, seems wanting.

## I. INTRODUCTION

The corpuscular theory of magnetic storms and aurorae was first proposed by Birkeland in 1896 [1]. He suggested that both these phenomena are due to charged particles emitted from the sun and that these particles are guided towards the polar regions by the geomagnetic field. This hypothesis found support in his experiments in which cathode-rays projected towards a magnetized sphere were seen to impinge along two zones, one around each pole of the sphere.

These experiments led Störmer [2] to study mathematically the motion of a single charged particle in the magnetic field of a dipole—which is a good approximation to the geomagnetic field except near the surface. The trajectories derived by Störmer showed many analogies with the forms of the aurora; nevertheless the theory is unsatisfactory in so far as it takes no account of the electrostatic forces which arise when many particles are present. These forces far exceed the deflecting force on a single charge by the geomagnetic field. In a cloud consisting of charges of one sign only the mutual electrostatic repulsion of its parts would disperse the particles to a negligible density long before their arrival at the distance of the earth.

To overcome this destructive criticism, first directed by Schuster [3] against one-signed corpuscular theories Lindemann (Lord Cherwell as he became later) in 1919 put forward [4] the suggestion that the streams emitted by the sun are neutral though ionized. He discussed at some length the process of emission, the speed attained by the particles of the stream and showed that the number of recombinations of ions and electrons to be expected during the passage of the stream from the sun to the earth was negligible. But he did not consider the phenomena which would develop during the advance of the stream in the geomagnetic field. Chapman and Ferraro [5] made the first attempt to develop a theory of magnetic storms based on the neutral stream hypothesis, and this will be described here. An entirely different theory, also based on the neutral stream hypothesis, was later proposed by Alfvén [6, 7]. But because of the neglect of the powerful electrostatic forces between the ions and electrons, the bearing of his theory on magnetic storms, like that of Birkeland–Störmer, is uncertain.

The evidence for a corpuscular theory of magnetic storms and aurorae had long been adduced by Maunder [8] and Chree [9] on the basis of the 27-day recurrence tendency shown by these phenomena. But this evidence was indirect and not indisputable until Meinel [10] showed from his observations of the auroral spectrum that high-speed protons were entering the upper atmosphere along the magnetic lines of force of the earth's field.

## 2. THE NEUTRAL IONIZED GAS

Observations of the solar atmosphere shows that from time to time gas is accelerated away from its surface. The long coronal streamers seen at the time of a solar eclipse is also taken as evidence of solar corpuscular emission. But as yet we do not know from what level in the solar atmosphere the neutral gas is emitted nor the mechanism of emission.

Great magnetic storms, however, are closely associated with intense solar flares. About a day after the occurence of such a flare the magnetic storm begins suddenly. This time lag is usually interpreted as indicating that the neutral gas travels from the sun to the earth with a speed of 1000–2000 km/sec. Since magnetic storms seldom occur if the flare is more than about 45° from the centre of the disc it is supposed that the angle of emission of the stream is large, ranging from about 40–50°.

Moderate and weak storms show a tendency—not shared by great storms—to recur after a period of a solar rotation of about 27 days. This recurrence tendency was interpreted by Maunder [8] as indicating a continued emission, lasting for a month or more, of gas from particular disturbed regions of the sun. Bartels has labelled these M regions. They are not always associated with sunspots.

Because these moderate storms do not begin abruptly it is difficult to infer the speed of M region streams. The evidence suggest that it is lower than for flare streams and lies probably in the range 500–1000 km/sec.

The gas is likely to be typical solar atmospheric gas, that is, mainly hydrogen atoms (mostly ionized) with a small admixture of other elements, notably $Ca^+$. The density and temperature are unknown: if the gas is emitted from the lower chromosphere the temperature is about 6000 °K, and the density of the order of $10^{10}$/cc. If the emission take place from a higher level the temperature will be correspondingly higher and the densit lower.

During its passage from the sun to the earth the stream will expand because of geometrical broadening and because of thermal velocities of the particles in the gas. For a gas at 6000 °K the velocity of expansion of the surface on this account is 11 km/sec; for the temperature of the corona it is 130 km/sec. If unimpeded during its passage from the sun to the earth, the stream would expand to linear dimensions of the order of $10^6$ km whatever the original size. The expansion due to geometrical broadening (produced by the divergent directions of emission at the sun's surface) will be still greater. For a conical angle of 20° the breadth of the stream at the distance of the earth is $5{\cdot}4 \times 10^7$ km. For a flare-burst stream it is still greater. This expansion will reduce the density by several powers of ten in the neighbourhood of the earth, depending on the original size and mass of the stream.

As seen from the earth the undisturbed stream surface will appear to be nearly plane. For a flare-burst stream this surface may be normal to the direction of travel of the particles in the stream. For an M region stream, the longitudinal surface of the stream is inclined to this direction (which is nearly radial from the sun) so that the stream overtakes the earth in its orbit once every 27 days with a speed of about $4 \times 10^7$ cm/sec. If the streaming velocity of the particles is $10^8$ cm/sec the stream surface will be inclined to the sun-earth line at an angle of about 20°.

## 3. INFLUENCE OF SOLAR AND INTERPLANETARY MAGNETIC FIELDS

Several suggestions have been put forward as regards the mode of emission of solar streams. Milne [11] supposed that it was due to the action of selective radiation pressure on certain chromospheric gases and showed that this process could accelerate the particles affected to speeds of about 1600 km/sec. This accords well with the estimate derived from solar terrestrial relationships. Kahn [12], however, questioned whether the available radiation would suffice to accelerate the particles away from the sun in sufficient numbers. Kiepenheuer [13] applied the Milne mechanism to solar flares and showed that it could account for the emission of $Ca^+$ ions in sufficient numbers if one makes reasonable assumptions about the energy output of the flare. Unfortunately, the mechanism is inapplicable to hydrogen atoms which are by far the most important constituent of the solar streams. Alfvén [6] has attributed the emission to the presence of a general solar magnetic field.

But, it is difficult to be certain of the influence of solar magnetic fields during the period of emission of the gas. Unless the gas is emitted along the direction of the magnetic lines of force of the sun's field, the latter will tend to hinder the passage of the gas outwards. If the gas be polarized by the magnetic field so that the resulting electric field exactly balances the electromagnetic deflecting force on the charges, then provided the energy density of the stream is sufficiently large the gas will be able to pass freely outwards through the magnetic field. Let $\rho$ and $\mathbf{v}$ be the density and velocity of the stream at any point and $\mathbf{H}$ the intensity of the magnetic field. Then the electric field $\mathbf{E}$ required to balance the magnetic deflecting force on the charge is $-\mathbf{v}\times\mathbf{H}/c$, where $c$ is the speed of light. The condition that the stream should be able to pass through the magnetic field unhindered is that the kinetic energy density $\frac{1}{2}\rho\mathbf{v}^2$ should be large compared with the electrostatic energy $E^2/8\pi$ or $v^2H^2/8\pi c^2$, that is, $\rho$ must be large compared with $H^2/4\pi c^2$. This is a lower limit. It seems more likely that the polarization electric field will be unable to entirely balance the magnetic deflecting force on the charges. In this case the magnetic lines of force of the solar field will be carried along with the gas and if this is able to escape from the sun it may well carry with it a part of the solar magnetic field—general or sunspot. This will be the case if the kinetic gas pressure $\rho v^2$ much exceeds the magnetic pressure of the tubes of force, $H^2/8\pi$, that is, if $\rho$ is large compared with $H^2/8\pi v^2$. This is a more stringent condition unless the velocity of the gas approaches the speed of light. Considering, for example, a neutral cloud of ionized gas moving outwards with a speed of 1000 km/sec the cloud will be able to escape through a solar magnetic field of the order of one gauss if $\rho$ exceeds $4\times10^6$ protons/cc. Considerably higher densities or velocities would be needed to enable the gas to escape from the magnetic field of sunspots.

If the gas is able to take with it a part of the solar magnetic field and the gas and the magnetic field imprisoned within it move into a region where the magnetic field is weaker, the surface of the gas will expand because of the tendency of the tubes of force to swell out. The velocity of expansion is likely to be of the order of $(H^2/8\pi\rho)^{1/2}$ and so less than the streaming velocity of the gas and probably greater than the thermal velocities. Thus the gas will inevitably expand to the dimensions mentioned earlier. The intensity of the magnetic field imprisoned in the gas will be greatly reduced by the time the gas reaches the earth's orbit. We may estimate this reduction as follows: since the lines of force are frozen in the gas, the magnetic flux through an open surface consisting of fluid particles will be conserved. Using also the equation of continuity of mass we find that the magnetic field will be reduced in the ratio $(\rho/\rho_0).(l/l_0)$ approximately, where $l$ denotes a typical length and the suffix 0 refers to the values of $\rho$ and $l$ at emission. Since $\rho/\rho_0\sim(l_0/l)^3$, the reduction in the intensity of the magnetic field of the gas is likely to be of the order of $(l_0/l)^2$. As a numerical illustration, suppose that the linear dimensions of the gas at emission are of the order of $10^4$ km. Near the earth the breadth of the stream is likely to exceed $10^7$ km. Thus the magnetic field in the gas will be reduced by a factor of a million at least and may well be unobservable near the earth.

An interplanetary magnetic field may also affect the advance of a solar stream towards the earth. Supposing that the magnetic lines of force of the interplanetary field are nearly perpendicular to the direction of travel of the stream, electric currents will be induced in the surface of the stream which will prevent the magnetic tubes of force penetrating into the gas. These will be pushed forward by the stream surface and the magnetic pressure exerted by the tubes of force will tend to retard the surface of the stream and render it very sharp long before the stream comes under the influence of the earth's field. The reduction in speed of the stream surface will become appreciable only if the intensity of the interplanetary magnetic field much exceeds $10^{-4}$ gauss. Estimates based on cosmic ray considerations do not indicate a field greater than this.

Before leaving the subject of the constitution of corpuscular streams, reference must be made to a recent attempt by Bennett and Hulburt [14] to revive the Birkeland–Störmer auroral theory by proposing a new variant of the neutral stream hypothesis. In this it is supposed that a conical beam of approximately equal numbers of fast moving ions and electrons are emitted from the sun. As it moves through the corona, the electrons in the stream have the smaller momentum and thus undergo a greater longitudinal retardation than the positive ions during encounters with the coronal particles and so tend to lag behind. Hence the stream carries an electric current. But because electrons are lost from the beam in the process, it acquires a positive charge which is then supposed to be neutralized by slower interplanetary electrons. Because of the inhibiting effects of self-induction, however, the current appears to be limited [15] to the value $mu/e$, where $m$ is the electronic mass and $u$ the velocity of the ions. Unless there are several such streams formed, the maximum current is of the order of 100 amperes and this is too small to be of interest.

## 4. THE AVERAGE CHARACTERISTICS OF MAGNETIC STORMS

During a magnetic storm the magnetic effects in middle and low latitudes are characterized by a sudden, world-wide increase in the horizontal force within the period of a minute. This rise is maintained for a few hours afterwards and constitutes the *first phase* of the storm. Thereafter the horizontal force decreases to a minimum some 8–15 hr after the beginning of the storm, the minimum below the normal exceeding the initial rise above normal. This period is the *main phase* of the storm. The field then returns to its normal value before the onset of the storm at a rate which becomes progressively slower and may last for many days.

Over the polar regions the disturbance is far more intense than in the middle regions of the earth. The evidence points to the existence of a system of electric currents flowing in the atmosphere which includes narrow concentrated filaments called electrojets flowing along the auroral zones. The flow of current is nearly eastward over one half of each of the two auroral zones lying on the post-meridian hemisphere, and westward over the other half. The current is completed in the atmosphere mainly across the polar cap. The height of the auroral currents estimated from magnetic data seems to be of the order of 100–150 km; the height of the polar cap currents is unknown.

Whilst there can be little doubt that in the polar regions a part of the current-system flows in the atmosphere, the same seems unlikely to be true of the rest of the current-system. The magnetic data points rather to an extra-terrestrial system of currents as the cause of geomagnetic disturbance in middle regions.

## 5. THE THEORY OF THE FIRST PHASE OF A MAGNETIC STORM

We next consider what happens when a neutral ionized stream advances into the earth's magnetic field. The velocity of 1000 km/sec inferred from solar-terrestrial relationships is about one hundred times the sonic velocity. The motion is therefore hypersonic and can be deduced from simple Newtonian considerations. The density of the gas near the earth appears sufficiently low for the effects of collisions to be neglected.

The gas may be treated as one of infinite electrical conductivity provided that the linear dimensions of the stream are large compared with the skin-depth $d=(4\pi ne^2/m)^{-1/2}$, where $n$ denotes the number density of the gas, $e$ and $m$ the electronic charge and mass. This condition is amply satisfied since for solar stream $d$ is of the order of a kilometre at most. It follows therefore that during its advance in the earth's magnetic field the stream will be shielded from the geomagnetic field by surface electric currents induced by the field. The surface of the stream will be sharply defined since it offers resistance to the interpenetrations of the tubes of force of the earth's field.

The magnetic tubes of force exert a pressure of amount $H^2/8\pi$ over the surface of the gas; since this is compressible it will yield to this pressure and a hollow will be carved out by the magnetic field. In the equatorial plane the section of the hollow will be roughly parabolic in shape except far out where little distortion of the stream surface takes place. The apex of the hollow will eventually be brought to rest. The distortion of the stream surface elsewhere is more difficult to determine. In the early stages of the motion, when the stream is far away from the earth, the surface of the gas can be considered as plane and the form of the current lines are as shown in Fig. 1. The current intensity vanishes at the foci $A$ and $B$ and at these points the gas is not retarded; hence two horns will emerge and as the gas advances and its surface becomes distorted the position of the foci will change. It is difficult to infer the further development of these two horns, but, as Chapman and Ferraro pointed out in their original papers [5], matter passing through the horns seems likely to find its way to the polar regions. It seems unlikely that the gas emerging from the two 'horns' will gain speed and energy. The regions of the atmosphere most likely to be affected by this gas is the F-layer in the polar regions.

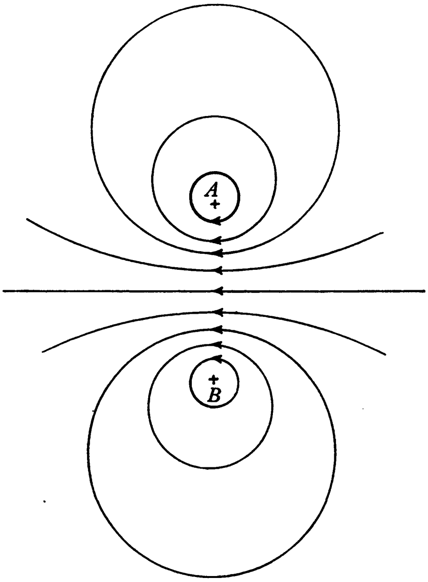

Fig. 1. Current-lines of the electric current-system induced in the front surface of the stream considered to be plane, parallel to the earth's dipole axis and normal to the direction of travel of the particles.

As the hollow in the stream deepens during the advance of the stream, more tubes of force are crowded together in it. The magnetic field in the hollow is thereby increased and would produce at the earth's surface a rise in the horizontal force. Chapman and Ferraro identified this increase as the beginning of the first phase of a magnetic storm. As long as the surface of the stream remains sensibly plane, the magnetic field of the induced currents adds to the earth's field a field equal to that of the image dipole of the earth. When the stream surface becomes highly distorted the rise in the magnetic field will be somewhat greater than the value calculated from the image dipole. It is possible to estimate the rate of diminution of velocity of the vertex of the hollow and hence the duration of the initial rise of the magnetic intensity during the first phase. The writer has shown [16] that it is of the order of a minute for an initial rise of about 20$\gamma$, as is, in fact, observed. The minimum distance $Za$ ($a$ being the earth's radius, $Z$ a numerical factor) from the earth attained by the vertex can be found by equating the kinetic gas pressure $\rho v^2$ to the magnetic pressure $H^2/8\pi$ on the stream surface or $H_0^2/8\pi Z$, where $H_0$ is the value of the horizontal field at the equator. Thus $Z=(H_0^2/8\pi\rho v^2)^{1/6}$ and so is very insensitive to changes in energy density. Taking the streaming velocity to be 1000 km/sec, the density of the stream at large distances from the earth necessary to produce an initial rise of 20$\gamma$ is inferred to be from 1 to 100/cc; and the minimum distance of approach about 5$a$.

## 6. THE RING-CURRENT AND THE THEORY OF THE MAIN PHASE

During and after the main phase of a magnetic storm the earth is surrounded by an external field which is nearly uniform and directed from north to south. The most direct explanation, and one which is supported by the magnetic records, is that this field is produced by a westward electric current flowing in a ring encircling the earth. This suggestion was first made by Störmer in a form which is untenable. It was revived by Schmidt [17] in 1924 purely on the evidence of the magnetic data. He thought that the ring was always present being re-enforced from time to time and that it decayed during periods of magnetic calm. He suggested that the ring is electrically neutral with the positive ions circulating westward and the electrons eastward. He gave no details as regards its size or the speed of the particles in it.

Chapman and Ferraro also attempted to explain the main phase of a magnetic storm on the hypothesis of a westward ring-current. They indicated how such a ring might be formed during a magnetic storm but their suggestion was little more than a qualitative sketch. They discussed the relative equilibrium, stability and decay of the ring and showed that there was no difficulty in accounting for the continued existence of the ring for many days once established. Chapman and Ferraro supposed that the ions and electrons would flow round the earth in the same sense and with very nearly the same speed. They pointed out that for any continuing ring the current must be westward because the radial acceleration towards the centre of the earth, necessary to maintain the motion, must be supplied by the ponderomotive force which the earth's magnetic field exerts on the current. Such a current would diminish the horizontal force at the surface of the earth as is observed during the main phase of a magnetic storm.

Alfvén [18] has questioned whether the ring would, in fact, be stable. He correctly states that the circular orbit of an isolated charge in the geomagnetic field is unstable since in the equatorial plane the field decreases more rapidly than the inverse square law, but concludes that the same is likely to be true for a larger assembly of charges. This conclusion is incorrect as is borne out by the discussion of an idealized problem devised by Chapman and Ferraro [19] to examine the radial stability of the ring-current. In this the ring-current is replaced by a cylindrical sheet of ionized gas and the earth's field is replaced by a unidirectional field parallel to the earth's axis and varying inversely as the cube of the distance from the axis. Let $H$ be the intensity of this field, $r$ the radial distance from the axis of the sheet, and write

$$H = H_0(a/r)^3, \tag{1}$$

where $a$ is the radius of the earth and $H_0$ the value of the earth's field at the equator. Let $\pm Q$ be the charges carried by the superposed ionic and electronic sheets, per unit length, $v_i$ and $v_e$ the azimuthal velocities of the ions and electrons in the sheet, respectively, and $m_i$, $m_e$ their respective masses. Define the azimuthal mass-velocity $v$ and the differential velocity $v'$ of the ions and electrons by the equations

$$mv = m_i v_i + m_e v_e, \quad v' = v_i - v_e, \tag{2}$$

where $m = m_i + m_e$. Then it can be shown [19] that the following equations hold

$$v = \frac{K}{r}, \quad v' = \frac{K'}{r} + \frac{eH_0a^3}{m''cr^2}, \quad m'' = m' + \frac{eQ}{c^2}, \tag{3}$$

where $m' = m_i m_e/m$ is the reduced mass of the charges and $r$ the radius of the sheet. The first equation expresses the conservation of angular momentum of the sheet about its axis. The second determines the currents induced in the sheet by its motion across the magnetic field. In addition we have the equation of radial motion

$$m\ddot{r} = \frac{mK^2 + m''K'^2}{r^3} + \frac{3eK'H_0a^3}{cr^4} + \frac{2e^2H_0^2a^6}{m''c^2r^5}. \tag{4}$$

The current per unit length of the sheet is $Qv'$ and the magnetic field, $H'$, which it produces within the sheet is equal to $2Qv'/cr$. Outside the sheet there is no additional field. It is convenient to write

$$mK^2 = \mu m'' K'^2, \quad r = aZ, \quad p = -eH_0 a^2/(m''cK'), \tag{5}$$

where $Z$, $\mu$ and $p$ are pure numbers; (4) may then be rewritten

$$\ddot{Z} = \frac{m''K'^2}{ma^4Z^5}\{(\mu+1)\,Z^2 - 3pZ + 2p^2\}. \tag{6}$$

We can interpret this as the equation of rectilinear motion of a particle in the field of force derived from the potential

$$U = \frac{m''K'^2}{2ma^4Z^4}\{(\mu+1)\,Z^2 - 2pZ + p^2\}. \tag{7}$$

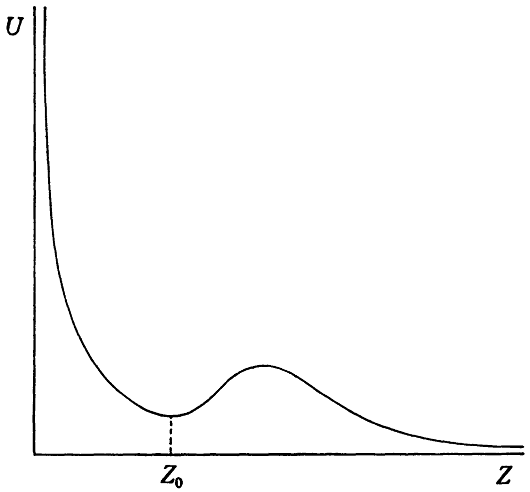

Fig. 2. Potential energy function for the radial motion of an infinite cylindrical sheet of ions and electrons in a unidirectional magnetic field whose intensity decreases inversely as the cube of the distance from the axis of the sheet. The position of stable relative equilibrium occurs at the minimum $Z_0$.

The positions of relative equilibrium of the sheet are given by the stationary values of $U$ if they exist. These occur for values of $Z$ given by

$$(\mu+1)\,Z^2 - 3pZ + 2p^2 = 0 \tag{8}$$

and the roots of this equation are real if $\mu < \frac{1}{8}$. This may be interpreted as an upper limit to the angular momentum of the sheet. When the positions of relative equilibrium exist the potential function has the form shown in Fig. 2. The stable position occurs for the smaller of the two values of $Z$ for which $U$ is stationary and a stable ring-current could be set up in this position. Its radius and the current within it would depend on the constants

$K$, $K'$, and $Q$, always provided that $\mu < \frac{1}{8}$. The magnetic field $H'$ ($= 2Qv'/cr$) produced by the current in the sheet can be expressed in terms of $Z$ and $p$ only (provided that $m'' \gg m'$ which is likely to be true in all cases of interest). Substituting for $K'$ and $v'$ from (3) and (5) in the expression for $H'$ quoted we find

$$H' = (2H_0/p^3)\left[\left(\frac{p}{Z}\right)^3 - \left(\frac{p}{Z}\right)^2\right] \tag{9}$$

approximately, since $m'' \gg m'$ implies that $m''c^2 \sim eQ$, by (3). From (8) the positions of stable equilibrium, $Z = Z_0$ say, is given by

$$\frac{p}{Z_0} = \frac{3 + \sqrt{(1 - 8\mu)}}{4}. \tag{10}$$

Clearly $3/4 < p/Z_0 < 1$, so that $H' < 0$ by (9), as was mentioned earlier in this section. The magnetic field of this current would thus produce a decrease in the earth's field at the surface. Near the limit of radial stability the roots of (8) become equal so that $\mu = \frac{1}{8}$ and $p = \frac{3}{4}Z_0$. In this case $H' = -2H_0^2/(3Z_0 3)$. For a moderate disturbance of about 30 $\gamma$ at the earth's surface the corresponding radius of the sheet would have to be about 8 earth radii. Chapman and Ferraro showed that no undue demands were made on the value of $Q$ or on the differential velocity of the charges of opposite sign, in all cases of interest.

In a ring-current, as for the sheet problem considered above, it is necessary that a radial electric field should act across the section of the ring and enable the ions and electrons to circulate round the earth together in the same sense. This electric field is produced by a slight separation of the oppositely charged particles under the action of the nearly equal and opposite forces acting on them. As was shown by Martyn [20] the maximum potential difference across the section may be of the order of four million volts. The polarization charges induced on the surface will thus be repelled from the surface along the magnetic lines of force and impinge on the polar regions with energies of the order of a million volts. This energy would suffice to account for the observed auroral penetration and occasion auroral luminescence.

## 7. THE ORIGIN OF THE WESTWARD CURRENT SYSTEM

The increase in the horizontal force produced by the currents induced in the surface of the stream (which is identified with the first phase of a magnetic storm) will be maintained so long as there is matter pouring into the current-layer from the shielded regions of the stream. If the depth of the stream is taken to be $5 \times 10^{12}$ cm, as seems likely, this increase could persist for as long as half a day if the speed of the particles is taken to be 1000 km/sec. Thereafter the horizontal force would rapidly return to its normal value before the onset of the storm, without reversal. Chapman and Ferraro therefore supposed that the ring-current would be set up whilst the earth was still enveloped in the stream. They suggested that soon after the hollow space becomes stationary the ring would begin to be formed by positive charges spiralling away from the walls of the hollow facing the anti-meridian side of the earth and bridging the gap at the back of the hollow. They thought that the current in this secondary stream, though feeble at first, would grow steadily. In order to bridge the gap the spiral radius of the ions, if these be protons, would have to be at least comparable with the breadth of the hollow. Taking this as 10 earth radii and the speed of the ions as 1000 km/sec the ions would begin to flow across the gap at a distance of about 60 earth radii. Although the current in the secondary stream would be westward, an estimate of its intensity suggests that it is too small to be of interest in this connexion.

It is possible that the westward current may be produced by the outward motion of ionized gas across the earth's magnetic field, as in the case of the first phase. Such an expansion of gas, atmospheric or interplanetary, may, under suitable conditions, give rise to the observed diminution of the field over the earth. A theory of this type in which the ionized gas is atmospheric has been advocated by Oliver Wulf and Vestine. An atmospheric origin of geomagnetic disturbance was suggested by Schuster long ago, but it has always been maintained that the observations lent little support to this hypothesis since there appears to be no noticeable difference in the mean intensity of the storm variations over the dark and sunlit hemispheres. An exception appears to be the station at Huancayo where the amplitude of sudden commencements, and possibly the first phase, are enhanced during daylight. Another criticism which may be directed against a purely atmospheric theory is that it would be difficult to account for the world-wide character of storms and the fact that occasionally marked similarities appear in the magnetograms at widely separated stations.

Nevertheless, if a substantial part of the material passing through the two 'horns' mentioned in section 5 finds its way into the earth's atmophere, mainly over the polar regions, the rate and amount of energy supplied by this material suffice to account for the observed rate of increase of the magnetic energy during the main phase. The energy is supplied at the rate of $\frac{1}{2}\rho V^3$, where $\rho$ is the density and $V$ the velocity of the gas. Taking

$V = 1000$ km/sec* this is equal to $0{\cdot}8N$ ergs/cm$^2$/sec, where $N$ is the number density of the gas. Supposing that this energy is absorbed along the two sunlit halves of the auroral zones, and taking their mean radius and breadth as 23° and 6° respectively, the energy supplied per second is of the order of $10^{17}N$ ergs/sec. Chapman and Bartels [21] give the rate of increase of magnetic energy during a storm as $2 \times 10^{18}$ ergs/sec. If one-tenth, say, of the energy added to the atmosphere were converted into magnetic energy the required density of the incoming gas would have to be about 200/cc, which is not excessive. To account for the world-wide character of magnetic storms this energy absorbed would have to be quickly redistributed over the whole atmosphere. This seems doubtful but the possibility cannot be ruled out.

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## *Discussion*

Alfvén: There are a few questions I want to ask here. First, why do you assume that the magnetic field decreases like $1/r^2$ when you have a beam of this type and you have a magnetic field with a component perpendicular to the

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* We have seen that there is little likelihood of the matter gaining speed or energy during its approach to the earth.

plane? The beam widens as $1/r$ and the magnetic field, assuming a constant velocity, should also decrease as $1/r$ which will give you a much higher magnetic field at the earth.

Ferraro: I rather think that there is a velocity spectrum along the stream as well and that the density decreases as $1/r^3$, not as $1/r^2$. I think that is much nearer the truth.

Alfvén: You assume a constant emission, and that the beam should be accelerated?

Ferraro: Yes.

Alfvén: But if it moves with constant velocity you have the magnetic field $H=H_0r_0/r$. If it doubles its velocity when it moves outwards the field is $H=H_0r_0/(2r)$, but not proportional to $1/r^2$.

Parker: I think Dr Ferraro is suggesting that the beam contains internal thermal motions which result in lateral accelerations in the beam, thereby decreasing the magnetic field more rapidly than $1/r$.

Alfvén: That cannot be correct in a model where a beam is assumed to go out radially, i.e. the way in which it is usually presented.

Parker: I do not think that this assumption is necessary.

Ferraro: My one feeling is that the inverse square law of the distribution of density is much too optimistic. I think the decrease should be more than this.

Alfvén: The second question is about the density. Let us assume, again, a radial emission such that the density $n$ in the beam is proportional to $\nu/r$, where $\nu$ is a constant. Then, you can calculate an upper limit for the density from the condition that the beam could not be denser and brighter than what can be observed in the corona. You could get an upper limit to the number of electrons in the beam, because you see the electrons in the corona by scattered light. If you consider the values of the density in the corona at different distances from the sun, you find that you have a high value near the solar surface but at a distance of about 4 or 5 solar radii you come to a minimum value of the constant $\nu$. If from the value you calculate the density at the earth's orbit you obtain about 20 particles/cm$^3$ which is an upper limit under the assumption that all the light of the corona is due to the beam. Under more reasonable assumptions you may come to a value of 2 particles/cm$^3$. This is a value which is much lower than the minimum value which is needed in order to explain the hollow and other effects in your theory. If you want to make the beam decrease with an expansion such as Parker mentioned this brings down the density value still more.

Ferraro: Oh yes, if you assume an expansion according to a $1/r^3$-law and assume $10^6$ particles in the beam you would come to a density of $1/\text{cm}^3$.

Alfvén: But do you not need $1000/\text{cm}^3$?

Ferraro: Yes, but this is for a great storm. I think that in our papers we estimated a density of 100–200/cm$^3$ to be necessary for a moderate storm.

Alfvén: But then you would see it, would you not?

Ferraro: Yes, but you really do not know from what level in the corona this emission takes place.

Alfvén: Perhaps not, but this argument will break down only in the case where you assume the beam to be emitted from more than 5–10 solar radii in the corona.

If it is emitted from that part of the corona which you could observe, the density could not be so high.

Ferraro: No, but why does it come from the corona?

Alfvén: Where does it come from otherwise?

Ferraro: We really do not know that.

Alfvén: Of course, you can let it be produced somewhere in the interplanetary space. That is all right. But then it has no connexion at all with the sun. You mentioned that the beam was supersonic but that collisions were negligible. Is that possible?

Singer: Would not the high density modify the present picture? If you take account of the fact that the cross-section is pretty large, would the picture really work at a density of $1000/\mathrm{cm}^3$? (The mean free path is less than 0·01 a.u.)

Ferraro: I am sorry I cannot answer this offhand.

Singer: Could you explain from your theory why the initial phase should have a duration of 8 hr?

Ferraro: I think the argument has been turned around here. The duration of the initial phase is used to estimate the depth of the stream.

Singer: Can you explain why the decay time of the ring-current is about 1–2 days?

Ferraro: Yes, this is due to the very great electromagnetic inertia of the ring.

Singer: What determines the time constant of the discharge in the auroral zones?

Ferraro: The time of leakage of the charges.

Lehnert: Have you investigated the stability of the ring-current in the axial direction?

Ferraro: No. That case we have not considered; it is very difficult mathematically.

Alfvén: The ring-current is introduced in order to explain equatorial disturbances. Now, the disturbances which you observe are not equally large at the day and night sides of the earth. Consequently, if you introduce a ring-current to explain equatorial disturbances it must be eccentric. This gives you a new type of instability because the forces cannot be balanced as far as I can see.

Ferraro: I think that this is a special case of the radial displacements which we have treated in our stability considerations.

Spitzer: Has anybody investigated the instability in the hollow; you have two gases of different density with a heavy one at the top?

Ferraro: I am afraid not. The problem is difficult enough already. It might be fairly stable and not break up into tongues.

Gold: It is important to consider the explanation of individual storms, not the mean effect. In any individual case there may be a factor of 3 or 4 in the magnitude of the movements at different longitudes in low latitudes, although they may be simultaneous. A distant ring-current can therefore frequently only explain a quarter of the effect, and the rest has to be more local, though still synchronized for some other reason. The ring-current at something like 4 radii would thus explain only so little that it is hardly worth invoking.

Ferraro: I think this is true but on the other hand it would be very difficult to explain the world-wide character of these disturbances. One way in which one could account for the differences in intensity at different stations would be to take into account the magnetic effects of possible current systems which actually could be present in the atmosphere. I think, however, that it would be extremely difficult to explain the total magnetic storms by currents flowing in the earth's upper atmosphere solely. I cannot see why we should necessarily reject the hypothesis of a ring-current simply because the intensities at various stations may differ by a factor of 2 or 3.

Dungey: I have a suggestion that the Chapman–Ferraro surface is unstable with respect to the formation of surface waves; it is just like wind over water. I think that this happens all the time. Due to the orbital motion of the earth the waves will travel eastward by day and westward by night. I suggest that this can be used to get one quantity referring to the 'winds' which Professor Alfvén has mentioned (*Proc. Ionosphere Conference*; Phys. Soc. (London, 1955), p. 229).

Block: I want to ask Dr Ferraro about the stability of the ring-current. I think we will agree that one single particle is unstable in the geomagnetic field.

Ferraro: Yes.

Block: Therefore you must need a minimum number of particles in the ring in order to get it stable. Have you ever calculated this minimum density?

Ferraro: It is in our paper of 1941. This density agrees quite well with that needed for the explanation of the first phase of a magnetic storm.

Block: When the ring-current is formed from the beginning, the density must be lower than this minimum density and then it is very difficult to understand how it can ever be formed at all, when it is not stable in the beginning of the formation.

Ferraro: These problems are very difficult and we have never claimed to show or to give a mechanism of how the ring-current is set up. On the other hand Professor Chapman has suggested an alternative way in which the ring-current can be formed. It is in a paper he has published in the *Indian Journal of Meteorology and Geophysics*. The idea is that some of the debris of the stream combine to form a ring-current in a way somewhat like the formation of a plasmoid of four jets that Dr Bostick has mentioned.