REVIEWS OF MODERN PHYSICS VOLUME 32, NUMBER 4 OCTOBER, 1960

Theory of Sudden Commencements and of the First Phase of a Magnetic Storm

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1. INTRODUCTION

THE corpuscular theory of magnetic storms and auroras was first proposed by K. Birkeland in 1896. He suggested that both phenomena were due to a stream of fast electrons emitted from the sun and that these were guided towards the polar regions by the geomagnetic field, there to give rise to the phenomenon of the aurora. He found support for his hypothesis in his experiments in which electrons projected towards a magnetized sphere were seen to impinge along two zones, one around each pole of the sphere. The theory was developed mathematically by C. Störmer who restricted his investigation to the motion of a single charged particle in the geomagnetic field which he approximated to a dipole. He showed that some of the trajectories had close analogies with the forms of the aurora.

Schuster in 1911 criticized the theory on the grounds that a beam of electrons could not hold together against the mutual repulsion of its parts. To overcome this destructive criticism, Lindemann, later Lord Cherwell, suggested in 1919 that the streams of particles emitted from the sun might be neutral but ionized, but did not consider the phenomena which would develop during the advance of the stream in the earth's magnetic field. Chapman and this author made the first sustained attempt to develop a theory of magnetic storms based on Lindemann's hypothesis. An entirely different theory was proposed by H. Alfvén who, like Birkeland and Störmer before him, neglected the powerful electrostatic forces between the ions and electrons.

In all these theories, interplanetary space was assumed to be a void; in recent years evidence has accrued showing that this is not the case and that there exists an ambient interplanetary gas with densities of the order of 100–1000 particles/cc. This gas, moreover, may not be stationary but endowed with a streaming motion radially away from the sun acquired by the continued emission of solar corpuscular streams.

It is shown here that no radical modifications seem necessary in our original theory of sudden commencements and of the first phase of a magnetic storm. The only modification is that the geomagnetic impulse due to the induced currents in the stream is propagated, not with the speed of light as we originally supposed, but with a finite speed which in the neighborhood of the earth approximates to the Alfvén velocity; this has already been noted by Piddington[1] and Dessler.[2]

2. THEORY OF THE FIRST PHASE OF A MAGNETIC STORM

During a magnetic storm the magnetic effects in middle and low latitudes are characterized by a sudden world-wide increase in the horizontal component H of the earth's field within the period of a minute. This rise is maintained for a few hours afterwards and this period of increase in H is called the *first phase* of the storm. The sudden onset of the storm is referred to as its *sudden commencement*. After the initial rise of the first phase, the horizontal force decreases to a minimum 8–15 hr after the beginning of the storm, the minimum below the normal level exceeding the initial rise above it. This period is the *main phase*. The field thereafter returns to its normal value at a rate which becomes progressively slower and may last many days.

We ascribe magnetic storms and auroras to the phenomena which develop during the advance in the earth's magnetic field of a neutral ionized stream of corpuscles emitted from the sun. The composition of these solar streams is likely to be typical solar gas, that is, mainly protons accompanied by electrons, their density and speed being very nearly equal. Because of geometrical broadening due to the divergent directions of emission of the particles, the size of the stream in the neighborhood of the earth is very large, of the order of 10^{12}-to 10^{13}-cm radius. The speed of the particles is usually inferred from the time lag of about one day between the occurrence of a solar flare and the sudden onset of a magnetic storm; this gives a speed of the order of 1000–2000 km/sec. Since the temperature of the solar gas ranges from 6000° in the photosphere to a million degrees in the corona, and since this is also likely to be the range in temperature to be expected in the solar streams, the streaming velocity of the particles are likely to be considerably larger than their thermal velocities. We accordingly neglect the random motions of the ions and electrons in the streams.

As the stream advances into the earth's magnetic field, electric currents are induced in the stream since an ionized gas is a good conductor of electricity; because collisions are negligible, the flow of currents takes place without resistance. It follows, therefore, that the magnetic flux across an open surface moving

[1] J. H. Piddington, Geophys. J. **2**, 173 (1959).
[2] A. J. Dessler, J. Geophys. Research **63**, 405 (1958).

with the stream particles remains constant, and if the flux vanishes initially it always does so. This was the case in our original form of the theory, since there was no reason to suppose then that the streams might carry any solar magnetic field away, so that the main body of the stream was supposed to be shielded from the earth's magnetic field.

In 1952 this author showed that the thickness of the current layer was of the order of the plasma wavelength, namely,

$$\delta=(mc^2/4\pi ne^2)^{\frac{1}{2}}, \tag{1}$$

where m and e are the electronic mass and charge, n the number density of the stream, and c the speed of light. The following values illustrate the variation of δ with n:

n	1	10	10^2	10^3
δ(in m)	5210	1650	521	165.

These values are small compared with the linear dimensions of a solar stream; the field variables can be shown to decrease to zero exponentially inwards from the stream surface in a distance of this order of magnitude. The body of the stream thus remains impervious to the interpenetration of the earth's magnetic field. Hence the particles of the stream in the shielded region travel in rectilinear paths with the undisturbed velocity of the particle at emission. In his 1952 paper, the author showed that the particles in the surface layers do, after a time, overtake those immediately in front so as to become the new stream surface; these in turn are overtaken by other particles so that the stream surface is continually reformed by new particles coming from the main body of the stream. In this way, the stream particles are able to penetrate further into the earth's magnetic field than would be the case if they were alone in the field. The distance where overtaking takes place is of the order of the Störmer constant C_{St} which, for protons traveling with speeds of 1000 km/sec, is of the order of about 150 earth radii.

The action of the magnetic field on the surface currents induced in the stream is to retard the motion of this surface. The retardation is greatest for those regions of the surface directly opposite to the earth. A depression therefore develops in the stream which deepens to form a hollow space in the stream surface. Because the tubes of force of the earth's field cannot penetrate the stream surface, they are crowded together in the hollow, thereby increasing the magnetic field in the hollow—an increase which we identify with the first phase of a magnetic storm.

The speed of the apex of the hollow v may be estimated by equating the rate at which momentum is destroyed in the surface layers of the stream to the magnetic pressure of the tubes of force on the surface. If $\rho(=nm_+)$ denotes the mass density of the positive ions, and v_∞ the speed of emission of the particle in the stream, we obtain

$$\rho(v_\infty-v)^2=H_s^2/8\pi, \tag{2}$$

where H_s is the magnetic intensity of the field at the surface of the stream. Thus

$$v=v_\infty-[H_s/(8\pi nm_+)^{\frac{1}{2}}] \tag{3}$$

and the apex is brought to rest ($v=0$) when

$$nm_+v_\infty^2=H_s^2/8\pi. \tag{4}$$

As far as orders of magnitudes are concerned,

$$H_s=fH_0(a/r)^3, \tag{5}$$

where f is a factor of order unit, r is the distance of the apex from the earth, a its radius, and H_0 the equatorial value of the earth's magnetic field. Hence, denoting by r_m the distance at which the apex of the hollow is brought to rest, and taking $f=2$, say, we find

$$r_m/a=(H_0^2/8\pi nm_+v_\infty^2)^{1/6}, \tag{6}$$

and (3) can now be written as

$$v/v_\infty=1-(r_m/r)^3. \tag{7}$$

Figure 1 illustrates the variation of v/v_∞ with r expressed in earth radii (Z). The maximum disturbance to be expected at the earth's surface is

$$H_m'=(\pi nm_+v_\infty^2)^{\frac{1}{2}}, \tag{8}$$

which for a stream consisting of protons and electrons moving with a speed of 1000 km/sec is

$$16n^{\frac{1}{2}} \text{ gammas.} \tag{9}$$

Thus a stream of particle density of the order of 10 protons/cc could produce a moderate disturbance (about 50 gamma) at the earth's surface. The corresponding value of r_m is about eight earth radii.

3. THEORY OF SUDDEN COMMENCEMENTS

As can be seen from Fig. 1, the diminution of velocity of the front surface of the stream to a small fraction of its initial speed takes place over a distance of a few earth radii. Because of the high velocity of the stream, the rise in the horizontal force is extremely rapid. This affords a direct explanation of the sudden commencement of a magnetic storm. For a stream composed of protons and electrons having a density of a few particles/cc and speeds of 1000 km/sec, the increase in H takes place in a time of the order of a minute. The sudden commencement observed at the earth's surface, however, is modified by ionospheric electromagnetic shielding and other factors, so that its time of propagation over the earth's surface is uncertain.

The speed of the particles in the stream was assumed to be the same for all, so that the stream surface remained sharp during its advance in the earth's magnetic field. If there exists a velocity distribution

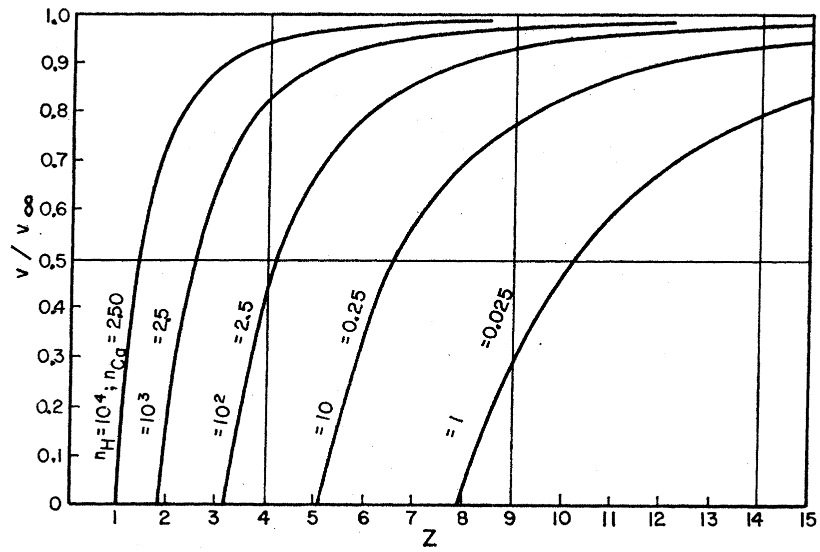

FIG. 1. Variation of the velocity of the stream surface v as a function of Z (the distance of stream surface from the earth in earth radii) for streams whose speed of projection is 10^6 cm/sec, and for various initial densities of the stream, in the cases when the ions are (i) protons, and (ii) calcium ions.

amongst the stream particles, the stream surface still tends to be sharply defined unless the density of the particles or their speed is so low that their motion becomes Störmerian. The limiting density below which the particles become Störmerian is most easily obtained by setting $r_m = C_{St}$ in (6).[3] We then find that

$$n_{\min} = (m_+^2 e^2 / 8\pi e^3 M) v, \tag{10}$$

where M is the magnetic moment of the earth, v the speed of the particles, and m_+ the mass of the positive ions. Taking $v = 1000$ km/sec and inserting numerical values for the various constants, we find

$$n \sim 10^{-7} \text{ particles/cc.} \tag{11}$$

Particles whose velocities lie in a velocity range higher than the streaming velocity but with number densities lower than the Störmerian limit calculated previously are swept up in the main body of the stream once this has entered the limit of the Störmer "forbidden region." Thus, it is clear that the streams which are able to penetrate to within a few earth radii from the earth develop a sharp surface during their advance into the earth's field.

4. MODIFICATION TO THE THEORY OF THE FIRST PHASE OF A MAGNETIC STORM

The theory of the first phase of a magnetic storm outlined in the foregoing was first put forward 30 years ago when there was no reason to believe that interplanetary space was anything but a void. Since then evidence has accrued that it is permeated by a highly ionized gas. In this section we consider what modifications are necessary to bring the theory into line with this discovery.

The long and regular series of small recurrent magnetic storms is evidence that interplanetary space cannot greatly influence the progress of solar corpuscular streams during their passage from the sun to the earth; and the low value of the critical density of the stream for Störmerian motions and the rate of retardation of the front surface of the stream make it clear that the important phenomena associated with the geomagnetic disturbance begin to develop at a distance of a few earth radii from the earth.

In the absence of the interplanetary gas the magnetic field of the current—roughly represented by an image dipole of the equivalent dipole of the earth's field—is propagated with the speed of light. Parker has rightly pointed out that one important effect of the interplanetary gas would be the slowing down of the rate of propagation of this field across the material and that if this were stationary the rate would be too slow to account for the development of a magnetic storm on any theory based on solar corpuscular streams. As was pointed out by Piddington[1] and Dessler,[2] the fact that the interplanetary gas is compressible means that the disturbance is propagated with a velocity of compression or longitudinal waves in the presence of a magnetic field.

Parker drew attention to the fact that the currents induced by the earth's magnetic field in the stream during its advance themselves induce equal and opposite currents in the interplanetary gas, and this would tend to mask the increase in the horizontal force which we identify with the first phase of a magnetic storm. The mutual repulsion between the stream and interplanetary gas currents prevents interpenetration of the two streams. In fact, the solar stream acts as a piston and compress the layers of the interplanetary gas in front of it; thus an induced shock wave is generated in the interplanetary gas. To simplify the mathematical discussion, we treat a one-dimensional model. The stream is supposed to be

[3] The value of $C_{St} = (eM/mvc)^{\frac{1}{2}}$.

moving parallel to the negative z direction and to be separated from the interplanetary gas by the plane $z=z_2$.

Let the quasi-shock wave advance into the interplanetary gas with speed v_s; let the common surface of the gas and stream advance with velocity v_2 and let ρ_2 be the gas density in the shocked region and ρ_1 that of the interplanetary gas. Let also H_2 and H_1 be the magnetic fields in these two regions. Then the equations of conservation of flow, momentum, and magnetic flux give

$$\rho_1 v_s = \rho_2(v_s - v_2) \tag{12}$$

$$\rho_1 v_s^2 + (H_1^2/8\pi) = \rho_2(v_s - v_2)^2 + (H_2^2/8\pi) \tag{13}$$

$$H_1 v_s = H_2(v_s - v_2). \tag{14}$$

The energy equation is not used, since this is embodied in (13). On writing

$$x = \rho_2/\rho_1 = H_2/H_1 = v_s/(v_s - v_2) \tag{15}$$

and substituting in (12)–(14) we find, omitting the root $x=1$ giving no shock, that x satisfies the cubic

$$(x+1)(x-1)^2 = 2xv_2^2/V_A^2, \tag{16}$$

where $V_A = H_1/(4\pi p)^{\frac{1}{2}}$, is the local Alfvén velocity in the interplanetary gas. This cubic has one negative and two positive roots, respectively, less than and greater than unity. The former must be rejected since this would make $v_s < v_2$. We may approximate to the other two roots in the two cases $v_2 \gg V_A$ and $v_2 \ll V_A$. The former obtains at large distances from the earth and the latter near the earth.

If $v_2 \gg V_A$, we find that x is large and approximately equal to $\sqrt{2}v_2/V_A$; this makes $(v_s - v_2)/v_2 \sim V_A/(v_2\sqrt{2})$ and thus small; that is, the velocity of the ideal shock is very nearly the same as that of the stream surface. When $v_2 \ll V_A$, the value of x is nearly unity and approximately $1+(v_2/V_A)$; the velocity of the ideal shock is then very nearly equal to the Alfvén velocity as was to be expected. For intermediate values of v_2/V_A, the values of x are of order unity; thus for $v_2/V_A = \frac{1}{2}\sqrt{3}$, the value of $x=2$, and for $v_2/V_A = \frac{2}{3}\sqrt{6}$ the value of $x=3$.

The momentum condition at the interface of the stream is unchanged and given by (2), namely,

$$\rho(V - v_2)^2 = H_2^2/8\pi = x^2 H_1^2/8\pi. \tag{17}$$

When x is large $(=v_2\sqrt{2}/V_A)$, this gives

$$v_2 = [\rho/(\rho_1+\rho)]V, \tag{18}$$

so that the interplanetary gas slows down the front surface of the stream approximately in the ratio $\rho/(\rho_1+\rho)$ of the velocity it would have in the absence of any interplanetary gas.

When v_2 becomes comparable with V_A, so that $x \sim 1$, the effect of the compression of the tubes of force becomes important and the retardation is mainly due to this.

The regular series of recurrent magnetic storms suggests, as has already been mentioned, that the interplanetary gas cannot greatly modify the motion of the solar streams at large distances from the earth. Thus we may expect that ρ_1/ρ is small, and that the stream density exceeds that of the interplanetary gas.

5. CHARACTER OF THE IDEAL SHOCK WAVE IN THE NEIGHBORHOOD OF THE EARTH

We must now consider more closely the motion of the quasi-shock wave in the neighborhood of the earth owing to the rapid increase of the earth's magnetic field in this region.

We suppose as before that the motion of the gas takes place in sheets normal to the z axis, that the motion is parallel to the negative z axis, and we replace the earth's magnetic field by a unidirectional magnetic field H_p varying inversely as the cube of the distance. Accordingly, we write

$$H_p = H_0(a/Z)^3, \tag{19}$$

where a is the earth's radius and H_0 the surface equatorial value of the geomagnetic field. This field could be produced only by a distribution of permanent magnetization in the y direction or by a system of currents in this direction.

Let ρ_2 be the density of the interplanetary gas; the compression of this gas by the solar stream is perpendicular to the plane face of the stream. The motion of an element of the interplanetary gas of coordinate z is governed by the equation

$$\rho_2 \partial^2 z/\partial t^2 = -(1/8\pi)(\partial H^2/\partial z) + F, \tag{20}$$

where F denotes the force arising from the presence of the magnetization or currents, namely, $(H/4\pi) \times (\partial H_p/\partial z_0)$, where z_0 denotes the initial values of z. Let also $\rho_2^{(0)}$ denote the initial value of ρ_2; then conservation of mass requires that

$$\rho_2 \partial z/\partial z_0 = \rho_2^{(0)}, \tag{21}$$

and since the magnetic lines of force are frozen in the gas, we also have the equation of constancy of flux, namely,

$$H \partial z/\partial z_0 = H_p. \tag{22}$$

On multiplying (20) by $\partial z/\partial z_0$ and using (21) and (22), we find

$$\rho_2^{(0)} \frac{\partial^2 z}{\partial t^2} = -\frac{1}{8\pi}\frac{\partial}{\partial z_0}\left[H_p^2\left\{\left(\frac{\partial z}{\partial z_0}\right)^{-2} - 1\right\}\right], \tag{23}$$

which is the required equation of propagation. To simplify the discussion we linearize this equation by writing

$$z=z_0+\zeta; \tag{24}$$

then (23) becomes very nearly

$$\rho_2^{(0)}\frac{\partial^2\zeta}{\partial t^2}=\frac{1}{4\pi}\frac{\partial}{\partial z_0}\left(H_p^2\frac{\partial\zeta}{\partial z_0}\right) \tag{25}$$

or, by (19),

$$\rho_2^{(0)}\frac{\partial^2\zeta}{\partial t^2}=\frac{H_0^2a^6}{4\pi}\frac{\partial}{\partial z_0}\left(\frac{1}{z_0^6}\frac{\partial\zeta}{\partial z_0}\right). \tag{26}$$

On writing $z_0=Za$, so that Z is nondimensional, this becomes

$$\frac{\partial\zeta}{\partial t^2}=\frac{H_0^2}{4\pi\rho_2^{(0)}a^2}\frac{\partial}{\partial Z}\left(\frac{1}{Z^6}\frac{\partial\zeta}{\partial Z}\right). \tag{27}$$

To solve this equation we assume $\zeta\propto e^{i\sigma t}$ and that $\rho_2^{(0)}$ is constant; the solution which is finite at the origin is

$$\zeta=AZ^{7/2}J_{7/8}(kZ^4/4), \tag{28}$$

where

$$k^2=4\pi\rho_2^{(0)}\sigma^2a^2/H_a^2 \tag{29}$$

and $J_{7/8}$ is the Bessel function of order 7/8.

6. NUMERICAL ILLUSTRATIONS

To illustrate the order of magnitude involved we assume that the values of the interplanetary gas density is constant and equal to about 1000 protons/cc up to two earth radii and that from this distance up to the top of the ionosphere, say, it increases exponentially to a value of 10^5 particles/cc at a height of 1000 km. On inserting numerical values for $H_a(=0.3$ gauss), $a=(6.38\times10^8$ cm) and $\rho_2=1000$ protons/cc, we find $k=0.55\sigma$. Earlier work mentioned in Sec. 2 indicates that the main stream impulse is produced at a distance of five earth radii in a time comparable with the time taken by the surface of the stream to traverse a distance equal to the earth radius. Thus we may set $2\pi/\sigma\sim6$ sec from which we have $k=0.58$; the argument of the Bessel function is then $0.162Z^4$. For $Z=2$ this gives 2.3, and up to this distance we may therefore approximate to the Bessel function by its asymptotic expansion, namely,

$$\zeta=2AZ^{\frac{3}{2}}(2/k\pi)^{\frac{1}{2}}\cos[(kZ^4/4)-(11\pi/16)]. \tag{30}$$

For distances from the earth smaller than two earth radii the density of the gas begins to increase and at a distance of 1000 km from the surface ($Z=1.15$), the density is of the order 10^5-10^6 at least. Thus, as a first approximation it may be assumed that ζ is given by (30). On substituting from (29) and introducing the time factor, we find

$$\zeta=2Az_0^{\frac{3}{2}}\left(\frac{2}{k\pi}\right)^{\frac{1}{2}}\cos\left(\frac{\sigma z_0}{V_A}-\sigma t-\frac{11\pi}{16}\right),\quad V_A=\frac{H}{[4\pi\rho_2^{(0)}]^{\frac{1}{2}}}, \tag{31}$$

whence it follows that the disturbance is propagated through the interplanetary gas with the local Alfvén velocity V_A. Also the displacement of any layer from its initial position is $\propto z_0^{\frac{3}{2}}$ and diminishes, but not too rapidly, as the wave approaches the earth.

Again, since $\partial\zeta/\partial z_0\sim3\zeta/2z_0$, the increase of the magnetic field is of the order of $\frac{3}{2}(\zeta/z_0)H$, which at a distance of two earth radii amounts to several hundred gammas even if $\zeta/z_0\sim0.1$.

7. TIME OF PROPAGATION OF THE DISTURBANCE THROUGH THE INTERPLANETARY GAS

We have seen in the last section that the disturbance is propagated through the interplanetary gas with the local Alfvén velocity. Thus the time of travel of the disturbances from the initial impulse at $z_0=z_s$, say, to the earth's surface $z_0=a$ is

$$t=\int_a^{z_s}\frac{dz_0}{V_A}=\int_a^{z_s}\frac{[4\pi\rho_2^{(0)}]^{\frac{1}{2}}}{H_p}dz_0. \tag{32}$$

We suppose that $\rho_2^{(0)}=\rho_1=$constant from $z_0=z_s$ to $z_0=z_i$, where $z_i<z_s$ and that $\rho_2^{(0)}=\rho_2\exp[-(z_0-a)/K]$ between $z_0=z_i$ and the earth's surface, with the continuity condition

$$\rho_1=\rho_2\exp[-(z_i-a)/K] \tag{33}$$

at $z=z_i$. On also writing $z_s=Z_sa$, $z_i=Z_ia$, and $K=ka$, we find

$$t=\int_{Z_i}^{Z}\frac{a(4\pi\rho_1)^{\frac{1}{2}}}{M_a}Z^3dZ+\int_1^{Z_i}\frac{a(4\pi\rho_2)^{\frac{1}{2}}}{M_a}Z^3\exp\left(-\frac{Z-1}{2K}\right)dZ$$
$$=\frac{a(4\pi)^{\frac{1}{2}}}{V_A}[\tfrac{1}{4}(\rho_1)^{\frac{1}{2}}(Z_s^4-Z_i^4)+p(1)(\rho_2)^{\frac{1}{2}}-p(Z_i)(\rho_1)^{\frac{1}{2}}], \tag{34}$$

where

$$p(x)=2kx^3+12k^2x^2+48k^3x+96k^4. \tag{35}$$

As a numerical illustration of the orders of magnitude involved, let $\rho_1=100$, $\rho_2=10^6$, $k=\frac{1}{10}$, corresponding to a scale height K of 600 km. On also taking $Z_s=5$, $Z_i=2$ we find $t=20$ sec so that the time of propagation is still fairly rapid, and corresponds to a speed of propagation double that of the streaming velocity. If $\rho_1=1000$ instead of 100, the corresponding time of travel would be raised to about 2 min.

DISCUSSION[a]

Session Reporter: R. A. Alpher

E. H. Vestine, *The Rand Corporation, Santa Monica, California:* Do you have any kind of an estimate of the size of the sudden commencement on the day side as compared to the night side, and also any concept of the probable variation of amplitude with latitude?

S. Chapman: I gave a paper with S. I. Akasofu last September in which we concluded that even at the equator the observed effects came partially from currents at a distance of several earth radii and partially from currents spreading down from polar regions. Analysis will be required to disentangle these.

R. V. Hess, *Langley Research Center, National Aeronautics and Space Administration, Langley, Virginia:* Could you discuss mechanisms responsible for velocities of protons and electrons greater than those in the solar stream? For example, for the fast electrons in the aurora, an accelerating mechanism using two stream instabilities has been suggested by Kellog and Liemohn.[b]

S. Chapman: In the streams we consider the particles have velocities of only 5 kv. There are 100-Mev protons in the van Allen belt. Either there is some powerful accelerating mechanism, or else high-energy particles are carried along by the solar stream and are trapped by some internal field in the stream.

R. Jastrow, *Goddard Space Flight Center, National Aeronautics and Space Administration, Washington, D. C.:* The auroral electrons are mostly less than 20 kv. The threshold of the trapped zone detectors has been about 20 kv. These detectors show a steeply varying spectrum which, together with one measurement at 10 kev, suggests that the bulk of electrons are at 10 to 20 kev. The 100-Mev protons are concentrated in the inner van Allen zone which is consistent with their being the products of β decay of backsplashed neutrons from cosmic rays.

The outer belt and auroral electrons are all soft. The spectrum of these eletcrons varies steeply from 10 to 50 kev, with few electrons above 30 kev. The hard protons occur at lower altitudes and latitudes with a spectrum consistent with their being placed in the inner belt by the β decay of backsplash neutrons.

A. R. Kantrowitz, *Avco-Everett Research Laboratory, Everett, Massachusetts:* What is the basis for the assumption that the temperature is everywhere zero? There is a tremendous streaming velocity. Professor Chapman says only one part per million of the energy is thermal to begin with. It would seem to me to require a miracle to prevent thermalization.

V. C. A. Ferraro: The particles see and feel the Lorentz force of the full magnetic field. This force deflects the ions so that the actual temperature does not matter as long as the thermal velocities are small compared with the streaming velocity. The actual deflection occurs in small steps. As the stream front approaches, particles in the leading layer suffer only small deflections before being overtaken by layers from behind. As Professor Chapman explained, the particle paths are nearly rectilinear until the particle velocities are perhaps half their original values. Until this point the curvature of the paths is extremely large. After this point the particles describe a motion characterized by the Larmor radius.

S. Chapman: There must be some thermalizing. At times we see matter shot from the sun at velocties of several hundred kilometers per second. Occasionally one sees the sun radiating neutral matter at velocities in excess of escape velocities. This matter presumably escapes at surface temperatures. If the solar streams reaching the earth have similar origin, and indeed even if the temperature is characteristic of the corona, the thermal energy is small compared to that of directed motion.

A. R. Kantrowitz: It would take an unlikely and extremely careful process to get these gases to such high velocity without heating. Apparently we do not really know the gas temperature.

On a former point, you consider the "shock wave" to be isentropic. Is not this an error similar to Riemann's error of 100 years ago, an error subsequently corrected by Rankine and Hugoniot when they added the energy equation to the system of equations?

J. M. Burgers, *University of Maryland, College Park, Maryland:* What Professor Ferraro considers is not an ordinary shock. The particles are specularly reflected by the magnetic field. Does the magnetic field do the randomizing?

A. R. Kantrowitz: The shock must be collision-free to achieve a steady state but such shocks must nevertheless involve an entropy change.

V. C. A. Ferraro: It is not a shock, but the conditions are as Professor Burgers has said. No pressure term is considered; particles are reflected by the field back into the stream. The equations here are similar to those in an earlier paper in which there was no interplanetary gas. Then we equated momentum destroyed to the change of magnetic pressure.

W. B. Thompson, *Atomic Energy Research Establishment, Harwell, Berkshire, England:* What you describe really seems to be the contact surface. How does the signal from the front of this contact surface propagate into the interplanetary gas and magnetic field? It must be by means of a shock.

V. C. A. Ferraro: What I have considered here is really a simpler case; the magnetic field is frozen into the interplanetary gas, and particles in the solar stream are turned back by the magnetic pressure. A more complete analysis must also involve the field varying properly with distance from the earth.

A. R. Kantrowitz: As was pointed out by Professor Gold some years ago,[c] it is necessary to have a shock to have a sudden commencement. Otherwise one must have a marvelously efficient acceleration process which does not heat the gas. If the process is such that an appreciable fraction of the expulsion energy appears as thermal energy, then the gas merely expands—its time of arrival being the time of expansion. Unless one has a miraculous cooling system to cool everything

[a] The discussion refers to the paper by V. C. A. Ferraro as well as to the preceeding paper by Sydney Chapman.
[b] P. J. Kellog and H. Liemohn, Phys. Fluids 3, 40 (1960); also see references of this paper.
[c] T. Gold in *Dynamics of Cosmic Clouds* (North-Holland Publishing Company, Amsterdam, 1955), p. 103

down, there must be a shock to cause bunching and to yield a sudden commencement.

V. C. A. Ferraro: A shock is not needed. The magnetic field collimates the gas and causes the leading surface to sharpen up as it advances into the field like a soft cushion being pushed against a wall.

V. N. Zhigulev, *Central Aero Hydrodynamic Institute, Moscow, U.S.S.R.:* I would like to call attention to a paper by Romishevskii and myself[d] in which we calculated the interaction of the interplanetary gas flow with the earth's magnetic field. The magnetic field of the earth is represented as a dipole inclined to the flow, and the calculaton was done in the hypersonic limit. Both the flow field and the distortion of the earth's magnetic field due to the flow were calculated.

[d] V. N. Zhigulev and E. A. Romishevskii, Doklady Akad. Nauk S.S.S.R. **127**, 1001 (1959) [English translation: Soviet Phys.-Doklady **4**, 859 (1960)].