ally correct, and can be used for the treatment of more complicated cases.

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New Theory of the Aurora Polaris

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A new theory is given to explain why the aurora generally appears in the form of one or more long thin ribbons or bands of light, in the east-west direction, mainly in high latitudes; and why, after its initial quiet diffuse phase, it breaks up into rayed bands, folded and pleated, simultaneous with the appearance of strong electric currents along the auroral zone. During the magnetic storm, when Earth is enveloped in a stream of protons and electrons from the sun, part of the gas is trapped in Earth's vicinity. New electric currents and their magnetic fields develop around Earth during such a period, and they modify Earth's field in such a way as to produce neutral lines. We associate each auroral band with the presence of a particular X type of neutral line of the magnetic field in or near Earth's magnetic equatorial plane. For auroral bands in a customary latitude such as 66 deg the neutral line is about 6 Earth radii from Earth's center. The transition from the first to the second auroral phase is ascribed to the growth of an eastward electric field and current along the neutral lines.

THE AURORA polaris is an intermittent luminescence of the ionosphere, most often visible in geomagnetic[3] latitudes above 60 deg. Many hypotheses have been proposed to explain it. It is now generally believed, on good evidence, to be caused by gas ejected from time to time by the sun in the form of streams or clouds. Their dimensions may greatly exceed those of Earth. The gas is neutral but ionized; it consists mainly of protons and electrons. The speed is of order 1000 miles per sec and the time of travel is about one day. Auroras, magnetic storms and other phenomena occur when Earth becomes immersed in such a solar cloud or stream. The flow of gas may envelope the Earth for hours or days (1).[4]

Within a distance of order 10 Earth radii from Earth's center[5] the motions of the solar particles are much influenced by the geomagnetic field. Those whose line of approach is more distant from Earth proceed almost undisturbed. Many of the particles that approach most directly are turned backwards, or deflected away to one or other side, at a distance of several Earth radii. Thus a hollow is formed in the stream. Some of the particles, however, become "trapped" in the field. Some particles travel to high latitudes and there enter Earth's atmosphere. If they penetrate to sufficiently low levels they produce auroral light, and also in certain conditions electric ionospheric currents that may strongly disturb the geomagnetic field.

The US and USSR satellites and cosmic rockets have revealed the presence, nature and some of the changes of the inner and outer "radiation belts" that encircle Earth (2, 3).

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[3] The abbreviation *gm* will here often be used to denote *geomagnetic*. In this paper latitude, Equator, axis, equatorial plane will in general signify *gm* latitude, *gm* Equator, *gm* axis, *gm* equatorial plane—all referring to the field of Earth idealized as that of a point magnetic dipole (whose axis is inclined at $11\frac{1}{2}$ deg to the geographical axis).

[4] Numbers in parentheses indicate References at end of paper.

[5] Distances from Earth's center will here generally be given in terms of the Earth's radius ($a = 6370$ km).

These belts, inner and outer, will here be referred to as V1 and V2 respectively. Both belts tend to decay, and are continually or intermittently renewed. For the V2 belt, the one of chief interest for the aurora, the rates of decay and renewal are decidedly variable. The energetic particles in the V2 belt, or at least the energetic protons, seem likely to come from the sun. Great changes in V2 have been observed during magnetic storms, when solar gas is flowing toward and past Earth.

The energetic particles of the belts circle around the lines of magnetic force. They also travel to and fro nearly along these lines, but with a sideways drift round Earth. The electrons drift eastward, the protons westward. These motions constitute an electric current encircling the Earth. This is commonly known as the (electric) ring current. Near Earth's surface it reduces the horizontal field component *H*.

In the early period of a magnetic storm *H* typically increases. This is ascribed to the relative motions of the solar particles near the surface of the hollow formed in the gas by the geomagnetic field. These relative motions constitute a distribution of electric current over the surface. The magnetic field of these currents may be denoted by *DCF* (*D* for disturbance, *CF* for corpuscular flux). The currents and the *DCF* field are strongest on the sunward side of Earth. They remain in being, doubtless with fluctuations, so long as the flow of solar gas toward Earth continues. The population and extent of the V2 belt vary during and after this onflow. We think that a third belt V3, outside the V2 belt, may be set up at such times (4). The energy of its particles may be below the limit of measurement with the instruments hitherto carried on the cosmic rockets. However this may be, the magnetic records taken at the Earth's surface show that the ring current is temporarily enhanced during magnetic storms. The additional field thus observed and produced may be denoted by *DR* (*D* for disturbance, *R* for ring current). After a few hours, at most, its growth overwhelms the *DCF* field at Earth's surface, so that during most of a magnetic storm the horizontal field *H* there is reduced. The *DR* field dies away in the course of days, after the maximum phase of the storm.

Thus when Earth lies in the path of a solar stream or cloud, conditions in the space within about 10 Earth radii around Earth are modified by the additional presence of solar particles, partly trapped and partly approaching and then passing away from Earth. Their motions influence the magnetic field in this large region—mainly by the addition of the *DCF* and *DR* field. Electric currents are also generated in the Earth's polar atmosphere, by the particles that produce auroras. Their magnetic field does not extend far outward in the space around Earth. It may be denoted by *DP* (*D* for disturbance and *P* for polar, because the currents appear to be generated in the polar regions).

Auroral Particles and Morphology

To understand the aurora polaris we need to know the nature, energy, flux and source of the solar particles that enter our atmosphere, and the details of how they produce the auroral light and the associated phenomena in the ionosphere. We need further to know why the solar particles enter the atmosphere in particular regions as observed, and why the inflow goes through cycles of change during auroral displays and magnetic storms. This last branch of auroral science may be called auroral morphology.

The Norwegian scientist Størmer, who made a lifelong study of the aurora, summarized his work and also in part the state of knowledge concerning it at the time (5). Chamberlain (17) is soon to publish a larger, more comprehensive treatise on the aurora and airglow. At a recent discussion on space science he remarked that only one attempt had been made to explain the morphology of the aurora. This attempt was made by Størmer, over a period of years of study of the motions of single-charged particles in the geomagnetic field. For the most part this field was treated, as is reasonable, as a dipole field. Many of his results seem encouraging and suggestive, but they cannot be regarded as explaining auroral morphology. One essential reason for this is that the auroral light and the associated magnetic disturbance require a flux of gas composed of charged particles in numbers far too great to permit their mutual electrostatic influence to be neglected.

Furthermore, recent rocket and spectroscopic observations suggest that most of the auroral light is produced by electrons whose energy is of order 30 to 100 kev (6). According to Størmer's theory, such electrons could enter Earth's atmosphere only within 4 deg from the geomagnetic poles.

We propose a new morphological theory of the aurora, which is different from Størmer's in several vital features. We do not claim to explain the full sequence of auroral causation by the solar streams and clouds. There remain gaps in our understanding of these events, and our theory involves one important ad hoc hypothesis, not yet independently established. In this respect the hypothesis parallels the inference—widely held over several decades, yet still not clearly proved or understood—that auroras and magnetic storms are caused by streams or clouds of solar gas.

Neutral Lines in the Magnetic Field

One of the most remarkable and distinctive features of the aurora is its typical form, an arc or "ribbon" of light (7). The ribbon at times extends for thousands of miles in a direction approximately normal to that of geomagnetic north, but its extent in height is measured in tens or at most hundreds of miles. Its thickness in the north-south direction is still less. The ribbon may be diffuse and quiet (8), or it may be marked by ray structure and folds, and be rapidly variable (9). The quiet diffuse form is about two or three miles thick; the rayed form is thinner, sometimes less than 500 yards thick.

An auroral arc may appear singly, or two or more may be visible at the same time. The transition from the quiet diffuse form to the actively changing rayed forms marks a definite stage in the course of an auroral display.

Two important phenomena of auroral morphology which pose problems are the ribbon appearance and the location of auroras, and the transition from the quiet to the active stage.

The auroral rays lie along the local lines of magnetic force. The quiet diffuse arc also conforms to the direction of these lines. The auroral particles clearly follow the magnetic lines as they enter our atmosphere. Suppose we were to travel outwards along a line of force, starting from a diffuse or rayed auroral arc. The line of force will curve downwards, approximately in a *gm* meridian plane, to the plane of the *gm* Equator. If it starts in a typical auroral latitude, e.g., 66 deg N, it will cross the Equator at a distance of $6\frac{1}{4}$ Earth radii (about 25,000 miles) from the Earth's center; thence it will proceed onward and reach the antarctic atmosphere at 66 deg *gm south* latitude. Such a line of force lies well beyond the main part of the normal V2 radiation belt, which extends to about 15,000 miles. But during strong magnetic disturbance this belt may extend outwards to or beyond this distance.

Consider next the course of *two* such lines of force associated with an auroral arc (66 deg *gm* latitude). Suppose one lies in the southerly "face" of the auroral arc or ribbon, and the other, in the same meridian, on the northerly face. The lines of force diverge, until the distance between them reaches a maximum in the plane of the magnetic Equator; then they converge to the same distance as at first, when they enter the antarctic atmosphere. For each mile or yard of thickness of the auroral ribbon, the distance between the lines at the equatorial plane is 29 miles or yards respectively. If the particles that produce the auroral ribbon travel along the lines of force, they must come from this very small "slice" of the V2 belt. But the total thickness of the belt is many thousands of miles. What can cause so striking a limitation of the source region of these auroral particles?

To this question we answer: the determining feature is the magnetic field. More particularly, we attribute the limitation to the presence of a certain type of *neutral line* in this field. A neutral *point* of a field of force is one at which the intensity vanishes; at such a point the field can have no direction. But neutral points are of two kinds, which we may call *O* points and *X* points (Fig. 1). By definition, an *O* neutral point is one at which the magnetic potential has a local maximum or minimum. At an *X* neutral point the potential declines outwards in some directions and increases in others. Lines of force can pass through an *X* point, where they will make a sharp change of direction. No line of force can pass through an *O* neutral point.

A neutral line is one of which every point is a neutral one. It may consist wholly of *O* neutral points: in that case it is called an *O* neutral line. Similarly it may be an *X* neutral line, consisting wholly of *X* neutral points. Or a neutral line may be partly *O* and partly *X*.

An *O* neutral line is *encircled* by lines of magnetic force, which shrink to zero radius as the line is approached. At any point *P* of an *X* neutral line, two lines of magnetic force approach it from opposite directions, and two other lines of force leave it in opposite directions. The tangents to these lines, at *P*, all lie in the plane through *P* normal to the neutral line. In free space, devoid of electric current, the angles between the tangents to the approaching lines of force and the receding lines of force are 90 deg; but if there is volume flow of electric current in the region of the *X* line, these angles may have other values.

A dipole field has no neutral lines (and consequently no such lines were involved in Størmer's attempts to explain auroral morphology). If neutral lines appear near Earth during periods of auroral and magnetic disturbance, they must be caused by the additional electric currents and magnetic fields then present. These flow partly near the surface of the hollow carved by the geomagnetic field in the flowing solar gas, partly in the whole volume of the radiation belts, and partly in the ionosphere. In addition the solar gas may carry within it a magnetic field (*DSM*)[6] transported away from the sun. The corresponding contributions to the magnetic field are those already denoted by *DCF*, *DR* and *DP*, together with *DSM* if present. The appearance of a neutral line or of neutral lines in the magnetic field near Earth we ascribe mainly to the *DR* field due to the ring current of the radiation belts. The *DCF* field makes a smaller contribution to the total field, but one to which we attribute considerable significance. The *DP* field, on the contrary, is likely to be too weak, at the distances of a few Earth radii where the neutral line(s) appear, to have any serious effect on their occurrence or form.

At times when no solar gas is flowing toward and past Earth, the radiation belts and the associated ring current distribution seem likely to be symmetrical about the geomagnetic axis. The *DR* field will in general have a direction different from that of the normal geomagnetic field—which for brevity we may call the *M* (main) field. Only in the equatorial plane, which is also the plane of the ring current, are the two fields parallel, namely normal to the plane. In this plane, outside the ring, the *DR* field has the same direction as the *M* field, because the ring current flow is westward. There the *DR* field strengthens the *M* field. Within the circular center line of the ring, it weakens the *M* field. Only there is it possible for the *DR* field to annul the *M* field and produce a neutral line of the combined field. For this to happen, the ring current electric flow must be sufficiently intense and suitably distributed over its cross section. The determining factors are the population and distribution of the energetic particles of the radiation belts.

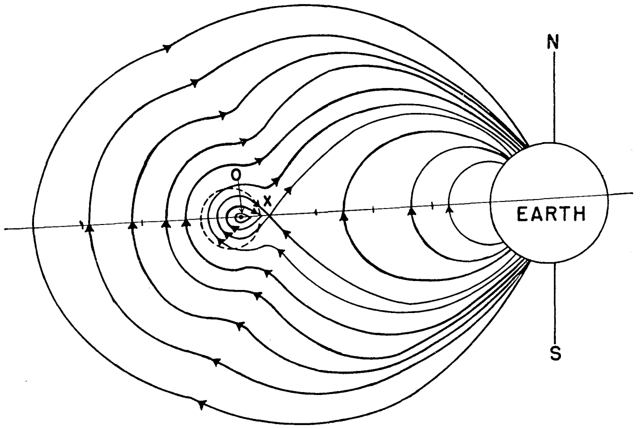

Fig. 1 Lines of force in geomagnetic meridian plane of Earth, when magnetic field is disturbed by a ring current. The circular cross section of this current is shown by broken line. Points *O* and *X* are the points where the resulting *O* and *X* neutral lines cross plane of diagram. Line *NS* is Earth's magnetic axis

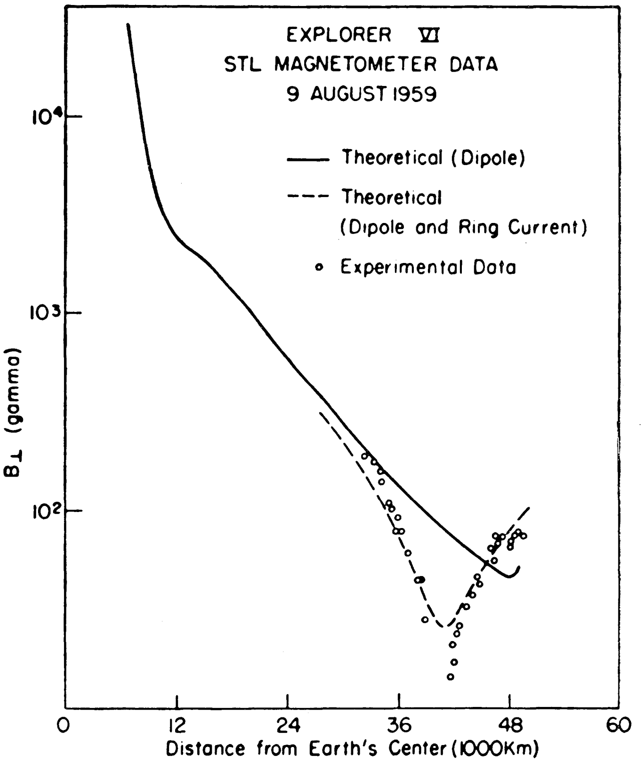

Fig. 2 Small circles indicate measurements made by US Satellite Explorer VI of magnetic field component perpendicular to its spin axis. At about 6 Earth radii they fall much below normal intensity of geomagnetic field (full line). Broken line indicates possible field reduced by presence of a ring current (courtesy of C. P. Sonett et al.)

A decrease of the total field intensity *F* below its normal main field value has been recorded by several cosmic rocket magnetometers, as follows: *R'* is the distance beyond which the field intensity was found to be reduced; *R* is the indicated radius of the ring current; both are expressed in Earth radii (see the table).

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[6] *D* stands for disturbance, *SM* for solar magnetism.

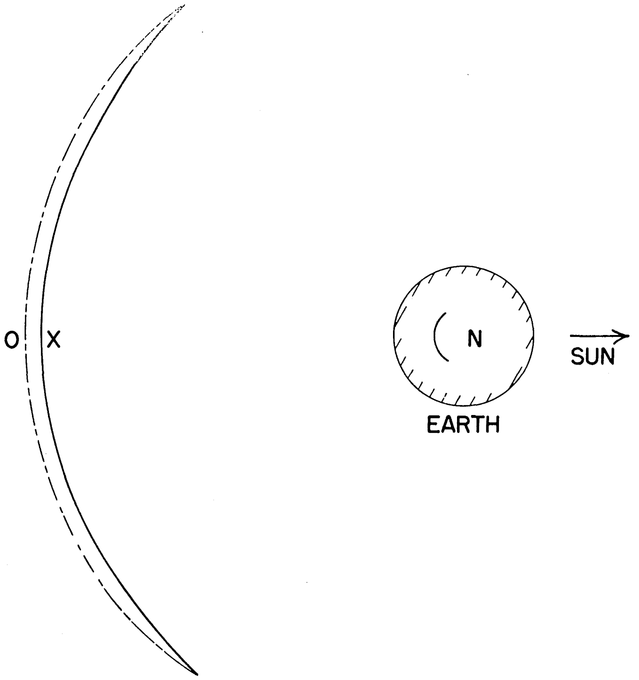

Fig. 3 Typical loop formed by an O- and X-type neutral line in geomagnetic equatorial plane, during magnetic storm. Radiation belt protons and electrons travel from vicinity of X neutral line and produce an auroral arc as shown on plan of Earth

Explorer VI recorded a deep minimum of F at about 6.4a (Fig. 2). All three US rockets indicated a region of severe fluctuations of F between 12 and 15a (10).

None of these observations has disclosed the presence of neutral points or lines. For several reasons this was not to be expected. Such presence is likely only during auroral displays, and in the magnetic equatorial plane, mainly on the side of Earth away from the sun. The rocket orbits did not lie in this plane, and the rockets were on the sunward side of Earth when they recorded the decrease of F. There a decrease was to be expected, but not a decrease to zero. It will not be easy to verify by rocket measurements that at times F sinks to zero along certain lines. To do so, the rocket orbit, if not in the magnetic equatorial plane, must intersect it at a point on the neutral line at just the time when this lines passes through that point. It should be possible, however, to detect exceptionally low values of F at points not too far from the neutral line or lines. Perhaps the best chance of neutral line detection would be given by a long-lived satellite with very elongated orbit, in or close to the plane of the geomagnetic Equator. The orbit should extend outwards to at least about 7a.

During a magnetic storm, the expected normal symmetry of the radiation belts and the ring current relative to the geomagnetic axis may be modified by the *DCF* field which is largest near the surface of the hollow in the day side. This asymmetry may distort the form of the ring current. It may cause the center to depart slightly from the *gm* axis, and may even slightly shift the plane from that of the *gm* Equator. The latter seems most likely to happen, if at all, when the sun's direction departs furthest from this plane. This will be at or near the solstice, at hours when the *gm* axis is tilted furthest from the sun's direction.

On the basis of present rocket observations of the radiation belt we cannot certainly predict that the observed growth of the *DR* field of the ring current will produce neutral lines. But there seems no inherent improbability in their appearance.

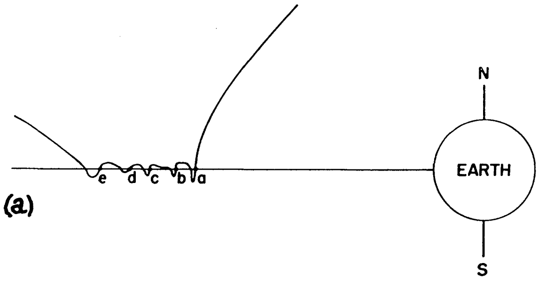

Fig. 4a Schematic graph of intensity of disturbed magnetic field along an equatorial radius from Earth, in midnight meridian plane, during magnetic storm. Marked points a, b, c, d and e are X-type neutral points; each is associated with an O-type neutral point on same equatorial radius

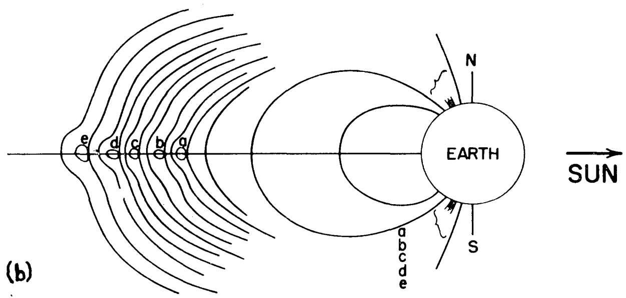

Fig. 4b Schematic diagram of magnetic field lines in midnight meridian plane of Fig. 4a. Protons and electrons travel along the lines from X-type neutral lines a, b, c, d and e and produce parallel auroral arcs in Earth's ionosphere, as indicated in diagram

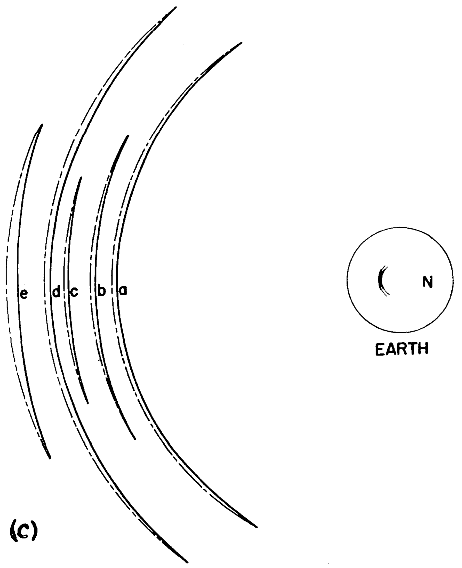

Fig. 4c Schematic diagram of the five loops formed by X-type neutral lines a, b, c, d and e of Figs. 4a and b, and by associated O-type neutral lines (broken lines). All these lines lie in or close to Earth's magnetic equatorial plane. Auroral arcs associated with the X-type neutral lines are indicated on Earth

Rocket	Launched	R	R'
USSR Mechta	1959 Jan. 2	2	3 or 4
US Pioneer I	1958 Oct. 11	5	9 or 10
US Explorer VI	1959 Aug. 7	5	9 or 10
US Pioneer V	1960 March 11	5	7 or 8

If they are present also at times when there is no solar stream, they are likely to be complete circles, surrounding the earth. If present only during the solar onflow, the neutral line may generally not completely encircle Earth. This is because of the *DCF* field in the equatorial plane, most intense on the sunward side. Thus storm conditions favor the presence of a neutral line on the dark side. Depending on the strengths of the *DCF* and *DR* fields, the neutral line may be confined to a small arc on the dark side, or extend over any larger angle up to complete encirclement of the Earth.

Fig. 3 shows a typical neutral line of limited angle, produced by a suitably intense toroidal ring current, symmetrical about the *gm* axis, in the presence of a *DCF* field of a certain intensity. The neutral line consists of a loop; the inner part, nearest Earth, is an *X* line, the remainder is an O line. Fig. 1 shows schematically the form of the lines of force of the combined field in the meridian plane that bisects this *OX* loop. Between the *O* and *X* lines the field direction is southward instead of northward (see Fig. 3).

The radiation belt is not toroidal, and the observed irregular distribution of its field beyond $10a$ implies an irregular distribution of the ring current. At such times it is natural to expect that in the region where the field intensity is low there may be more than one reversal of the field. Thus the *H* distribution along a radius in the equatorial plane, and the form of the field lines in the meridian plane, might instead be as in Figs. 4a and 4b. This shows five pairs instead of only one pair of neutral points (intersections with the neutral lines). Alternative simple typical forms of the whole set of neutral lines in (or near) the equatorial plane are shown in Fig. 4c. The pattern may at times be decidedly more complicated. The irregularities of the field may also distort some of the neutral lines slightly away from the equatorial plane. The pattern of these lines in or near this plane may be likened to the contour of the water surface on a lake, at its mean level, when the surface is slightly disturbed by winds or other influences. The rises or depressions of the surface, in this analogy, represent the northward and southward direction and intensity of the magnetic field in the equatorial plane. The pattern in the case of the neutral lines has a structure determined by the near symmetry of the electric current system around the *gm* axis. In the lake analogy, surface changes due to the throwing in of a stone would produce a circular pattern round the point of entry; wind might cause a less regular pattern.

Significance of the Neutral Lines for Auroral Morphology

The energetic particles of the radiation belts, as mentioned (1), circle around the local direction of the field intensity *F*. They also oscillate back and forth between northern and southern "mirror points." This oscillatory motion is along the *F* lines except for an additional sideways drift around Earth. The circular part of the motion causes the particles to modify the magnetic field as if they were small dipoles directed opposite to *F*. The equivalent dipole moment (μ) of a particle is proportional to Av, where *A* denotes the area of the circle it describes, and *v* the speed of motion round the circle. As the component motion along the field takes the particle into stronger or weaker parts of the field, *A* is respectively decreased or increased; the circle shrinks or expands. At the same time there is a compensating opposite change of the speed *v*, so that Av and the dipole moment μ remain invariant. But the total speed of the particle also remains constant. Hence the component speed along the field must decrease as the particle moves into a stronger part of the field. This retardation finally reduces this component speed to zero. The point where this happens is called a mirror point, because there the particle, still with the same dipole moment, turns back to return into regions of less intense field. This description of the motion is valid anywhere in Earth's undisturbed magnetic field for protons of their energy less than 5 Mev and all the electrons observed so far, at about $6a$.

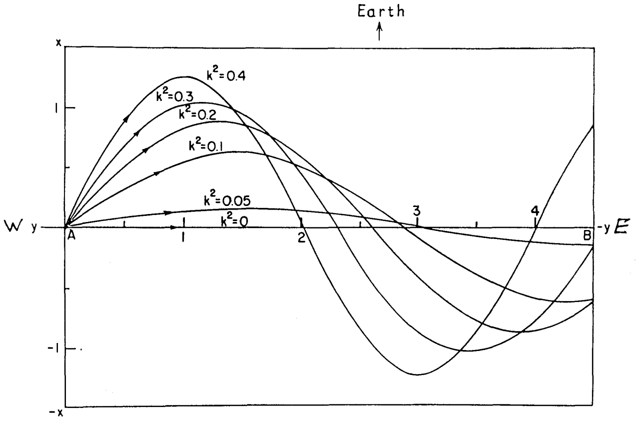

Fig. 5 Paths of protons near *X*-type neutral line in equatorial plane for various values of their inclination to neutral line at intersection. *AB* is part of neutral line; curvature of this line is too small to be shown here. Paths of electrons are similar but opposite in direction, with much smaller wave amplitude

The tiny magnets are very little affected by hydromagnetic waves (fluctuations in the field) for any amplitudes and frequencies to be expected there. They are liable to change, however, if they come close to any neutral line that may develop in the field during the magnetic storm. There the invariance of the dipole moment ceases to hold. Indeed very close to a neutral point, where the field is zero, there is no question of circular motion and dipole moment. A particle with a certain magnetic moment that approaches a neutral line closely will have a different moment after it leaves the vicinity of the line. Hydromagnetic waves can play an important role during the passage of a particle through the neighborhood of the neutral line.

The change in the character of the motion will first be illustrated in a specially simple case, that of a particle initially moving in the *gm* equatorial field near a neutral line. Within a narrow strip of the plane, bordering the neutral line on each side, the motion is no longer trochoidal, with curvature always in the same sense. Instead the motion is as shown in Fig. 5 (11). If the particle is displaced slightly from the plane, it will continue to move away from it. But now the component speed along *F* is accelerated instead of retarded.

Consider the alternative fates of a particle which at a given time *t* is at a point *P* in the equatorial plane, and moving with given velocity *v* in the plane. Imagine alternative states of the magnetic field near *P*. In state 1 the field there is normal, for example, the undisturbed dipole field. In state 2, additional *DR* and *DFC* fields produce a neutral line close to *P*. If the particle is given a slight impulse and velocity normal to the equatorial plane, in state 1 this velocity will decrease as the particle moves away from the plane. The particle will soon reach a mirror point, and will thereafter oscillate between it and a corresponding point on the opposite side of the plane. In state 2, on the contrary, the motion away from the plane is accelerated, and the particle travels further along the line of force before reaching a mirror point.

Next suppose that the particle, instead of initially moving in the equatorial plane, reaches this plane with a significant fraction of its velocity along the normal to the plane. Such a particle, in state 1 of the field, will have come from a mirror point well away from the plane. Let h_1 denote the height of the mirror point above Earth. In state 2 of the field, however, if the particle at *P* has the same velocity *v*, inclined to the plane, it will be accelerated away from the plane, with decreasing dipole moment. It will reach a mirror point at a smaller height h_2 above Earth. This level might be deep in the atmosphere, or even below the Earth's surface (h_2 negative). If so, when the air resistance becomes greater than the electromagnetic force on the moving particle, the motion will cease to conform to the equations valid for free space.

Thus the presence of the neutral line can enable a particle to contribute to auroral production, which in the undisturbed field would never approach auroral levels in the atmosphere.

This influence of the neutral line is confined to those particles that come close to it; the limiting distance for 30 kev electrons is about one-tenth of that for 130 kev protons. These energies are typical for the two kinds of particle as yet observed in the V2 belt. During a magnetic storm the *DCF* and, especially, the *DR* field may gradually change, so that the *X* neutral lines approach or recede from Earth. A particle that leaves the equatorial plane, moving northwards or southwards, from a "normal" point of the field may on its return find itself in the critical strip around a neutral line. Then it may travel into the auroral ionosphere, north or south, and be lost to the belt. A changing neutral line or lines may thus sweep up much of a certain region of the belt, with the flow to the auroral ionosphere at each moment confined to the thin space bounded by the magnetic field lines through the edges of the critical strip associated with the line or lines. If there is more than one *X* neutral line, as illustrated in Fig. 4, there will be a series of auroral ribbons, or arcs, as is often seen during displays.

Thus we interpret an auroral arc or arcs as indicating the presence, in the equatorial plane, of a neutral line or lines, linked with the auroral arc or arcs by field lines. The positions of the neutral line or lines in the equatorial plane can be inferred within narrow limits from the latitudes of the auroral arc or arcs, without taking into account the deviation of the lines of force of the disturbed magnetic field from those of the undisturbed dipole field.

The Auroral Breakup

A typical auroral display during a period of active *gm* disturbance has an initial quiet period followed by an active phase. In the former, the aurora is diffuse, and the arcs move slowly toward or away from the poles. Suddenly the display changes. Rays appear, the "ribbon" becomes thinner, and it becomes less regular and more mobile. Changing folds appear, forming "draperies" or "curtains." Superposed on these folds there is a finer corrugation or pleating of the "ribbon." The number of arcs, curtains or bands visible in the sky may increase. Evanescent rays may dart downwards, or ripples may flow eastward or westward along the bands. Viewed from a point on the ground, from which a line of force passed upwards *within* a great auroral fold, the rays in the curtain will be seen to converge toward the direction of that line of force. This convergence of rays may extend over a wide arc round this direction. Such a form is called a *corona*. It may cover a large part of the observer's sky, and be bordered by the edges and lower parts of more or less parallel auroral bands to north and south of the "observer's" fold.

At such times the bands are often tipped with red along their lower border, which extends deeper into the atmosphere than during the quiet phase.

We interpret this active phase of the aurora as indicating a change of conditions in and near the part of the equatorial plane where there are neutral lines. The particles still enter the auroral region from narrow strips or regions in this plane, bordering a neutral line or lines. But these strips are now narrower than before, and the neutral lines are wavy, corresponding to the folds in the auroral ribbons or bands. Like these folds, the waves in the neutral lines are quickly changing. New neutral lines may appear and disappear in a wide band of the plane, like new depressions on the surface of a lake dappled by breezes. The question naturally arises: what is the physical cause of this notable change of state in the equatorial band where the field intensity is low?

The explanation we offer is that weak electric currents flow eastward along the neutral line or lines during this phase. One consequence is to modify the field lines in the immediate vicinity of the neutral line or lines. Fig. 6a shows the form of the field lines near a neutral line, in the absence of such a current. Fig. 6b shows field lines of the additional field due to the current, and Fig. 6c shows the lines of the new compound field (12). The lines of force through the neutral line itself are no longer perpendicular. They become less inclined to the normal to the equatorial plane. Calculation shows that this narrows the strip centered on the neutral line, within which the circular motion of the particles can be partly converted into motion along the field, permitting the particles to penetrate the auroral ionosphere. Thus the auroral ribbons become notably thinner. They are reduced from two or three miles in thickness to only a few hundred yards.

The electric current implies the presence of an electric field along the neutral line. This accelerates the particles (especially the electrons) in the region near the line, increasing their energy. Consequently, when the accelerated particles leave the region to travel earthwards, their penetration into the auroral ionosphere is increased, as observed. The flux of electrons is enhanced, that of the protons is diminished. Slight changes in the distribution of other less energetic charged particles in the neighborhood keep net space charge densities to a low level.

The form of the magnetic field near the neutral line tends to confine the electric current toward this line. Constricted electric currents in a gas are known to be unstable; hence the wavy, changing structure of the current. This carries the neutral line with it in its fluctuations, thus explaining the folds in the auroral ribbon. However, these processes deserve further detailed study, for the conditions that obtain in the V2 or V3 belt during magnetic storms.

The finer corrugation or pleating of the auroral ribbon is explained as an instability of the thin curved sheets formed by the charged particles as they move from the vicinity of the neutral lines, along the magnetic field lines, into the auroral ionosphere. Instability of this kind in such sheets, due to the electrostatic forces between the particles, has been discussed by Webster (13) and demonstrated by his experiments.

Thus we explain the main features of the morphology of the aurora during its active phase by the hypothesis of an electric field along the neutral line or lines. At present this is a hypothesis ad hoc. It is somewhat on a par with the hypothesis, accepted over several decades, that magnetic storms and auroras are due to corpuscular streams and clouds from the sun.

As in the latter case, we cannot yet adequately explain how the electric field originates. But the one simple hypothesis accounts for several observed phenomena. These are not confined to the auroral features so far mentioned.

The difference between the flux densities of electrons and protons during the unstable phase produces a slight relative displacement of the two sets of charges in their overlapping curved regions of flow from the equatorial plane to the ionosphere. This produces an electric field in the ionosphere, usually directed equatorward. Because of the presence of the *gm* field, the electrical conductivity in the ionosphere at the auroral level is anisotropic (14). Hence this electric field associated with the influx of particles drives electric current *along* the auroral zone, usually westward. Strong magnetic disturbances (the *DP* field), which indicate the presence of such auroral electric currents, are a usual accompaniment of the active phase of auroral displays.

These *DP* fields and intense active auroras appear sporadically, and often suddenly, during magnetic storms. Their duration is only a fraction of that of the storm. More than one may appear in the course of a storm, at irregular intervals. We attribute both phenomena to the onset of an electric field along the neutral line or lines, due perhaps to the

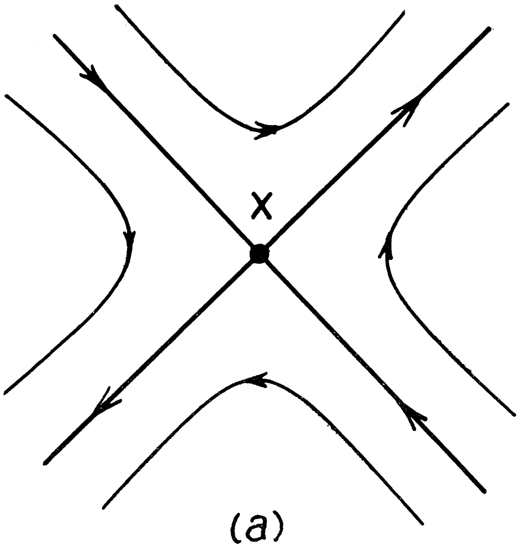

Fig. 6a Lines of magnetic force (in empty space) near X-type neutral line in the disturbed field present during magnetic storm. Point X is on night side of Earth; Earth and sun are outside diagram, far to right. Reader's line of sight to diagram corresponds to westward direction round Earth

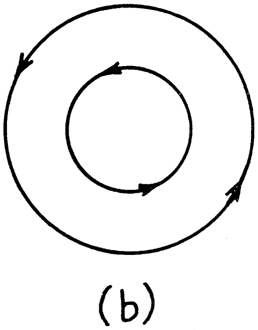

Fig. 6b Lines of force due to current flowing eastwards (upwards from plane of diagram) along neutral line

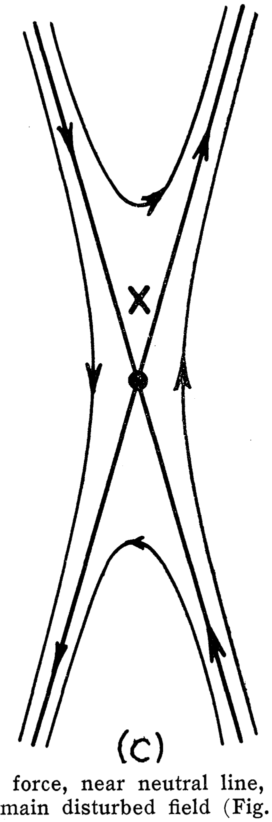

Fig. 6c Lines of force, near neutral line, of combined field corresponding to main disturbed field (Fig. 6a) and the field (Fig. 6b) of eastward current along neutral line

gensudden ulfing of a mass of solar gas in the V2 or V3 belt. This trapped mass, like the charged particles generated by the Argus nuclear explosions, will tend to spread all round the Earth, but during the spread, temporary electric fields in the belt region may be involved. The necessary electric field along the neutral line or lines is very small, of order 1 v per km.

During the development of a great magnetic storm and its associated auroral display, the ring current and its magnetic field *DR* increase to a maximum and then decline. As the *DR* field grows in intensity, the neutral line, mainly on the dark side of Earth, moves closer toward Earth. Correspondingly the northern and southern auroral arcs associated with it move toward lower latitudes.

The Final Auroral Phase

The final phase of a great auroral display is often fantastic. Isolated rays and pulsating patches of light appear and disappear over a large part of the sky, and there is no longer any arc structure. The field in the region of low intensity in or near the equatorial plane has lost its regularity of structure, owing to the instability of the electric currents along the neutral line or lines. To use the former metaphor, the dappling of the lake surface is entirely irregular, as might be caused by blustery eddying winds. Finally the influx of new solar gas trapped by the field becomes well distributed around the Earth. The electric field that is present while the gas is spreading from the trapping region dies away. The magnetic field settles down to regularity once more, with perhaps one neutral line present, with no electric field along it. The auroral cycle may begin anew, with a quiet diffuse arc. This may fade away if the *DR* field decays; or a new active display may later develop.

Concluding Remarks

Our theory is open to test in more than one way. It is desirable to try to check the presence and location of neutral lines in the field round Earth, by satellite measurements. Rocket magnetometers that can measure direction may be able to identify such regions of reversed field; they are, however, likely to be small, and the field is likely to be very weak there. Another check relates to the simultaneity and similarity of auroral appearance in the arctic and antarctic, at the ends of the same lines of force of the magnetic field. This check is possible only during the period when both regions are simultaneously in darkness. It requires observation, preferably by all-sky cameras, at northern stations linked by lines of force with one or more of the few available antarctic stations where all-sky photography is carried on.

If confirmed, our theory indicates that the occurrence of auroras is a fruitful source of information as to the magnetic and electric conditions in space near the *gm* equatorial plane, at distances of many Earth radii from Earth's center.

Appendix

This appendix gives tentative values of many quantities associated with our theory of auroral morphology. Some of these quantities are observed, many are inferred.

Solar streams and clouds

	Protons	Electrons
velocity	up to 2×10^8 cm/sec	up to 2×10^8 cm/sec
energy	up to 20 Kev[a]	$1 \approx 2$ ev[b]
number density[c]	100/cm^3	100/cm^3
flux	up to 2×10^{10}/cm^2 sec	up to 2×10^{10}/cm^2 sec

DCF field

	Location of the stream front[d]			
	4a	5a	6a	∞
intensity[e]				
at the front of the stream	500 γ	260 γ	150 γ	0
at Earth's surface				
dayside	93 γ	44 γ	24 γ	0
nightside	44 γ	24 γ	15 γ	0

DR field

Intensity at Earth's surface: up to 400 γ. (The induction effect is subtracted.)

Intensity of the *DR* field at Earth's surface for the production of a neutral line at 6 Earth radii must be about 20 γ.

Trapped particles: illustrative data at 6 Earth radii

	Protons	Electrons
energy	500 kev	30 kev
speed	10^9 cm/sec	10^{10} cm/sec
maximum E-W[f] drift speed	W 250 km/sec	E 16 km/sec
oscillation time[f,g]	23 sec	2 sec
time of revolution round the Earth[f]	24 min	6 hr
Oscillations per revolution[f]	63	10,100

Radiation belts and particles (16)

	Protons	Electrons
	Observed	
	V1, inner belt, at 1.5*a*	
energy	40 mev	20 kev
flux	2×10^4/cm² sec	2×10^9/cm² sec
	V2 belt, at 3.5*a*	
energy	60 mev	20 kev
flux	10^2/cm² sec	10^{11}/cm² sec
	Inferred	
	V3 belt, ring current belt, beyond 6*a*, in outer part of V2	
energy	500 kev	20 kev
flux	(?)	10^9/cm² sec

Auroral zone

	Location	Corresponding location in the equatorial plane connected by lines of force
center of the auroral zone[h]	66°30′ *gm* lat	6.3*a*
low latitude aurora[i]	down to about 55°30′	3.1*a*

Auroral particles in the auroral zone

	Protons	Electrons
diffuse form		
energy	150 kev	30 kev
flux[j]	5×10^5/cm² sec	10^7/cm² sec
active form		
energy	150 Kev	30 kev ∽ 250 kev
flux[j]	5×10^3/cm² sec	10^{11}/cm² sec
lines and bands produced	Hα	5577 (OI), 3914 (N_2^+), etc.

Auroral particles in the equatorial plane; at 6 Earth radii

	Protons (100 kev)	Electrons (30 kev)
radius of gyration	180 km	1.7 km
period of gyration	0.26 sec	1.5×10^{-4} sec

Auroral curtains

length, at least 2000 km

thickness

	Proton layer (Hα layer)	Electron layer
diffuse form	30 km	3 km
	(700 km)[k]	(70 km)
active form	30 km (?)	250 m
	(often invisible)	(6 km)

rregularities

	Characteristic length	Cause
large scale irregularity (folded structure)	10 ∽ 500 km	instability of the neutral line
small scale irregularity (ray structure)	1 ∽ 4 km	instability of the thin electron beam-sheet

lifetime

diffuse form	1 ∽ 5 days (intense display)
active form	1 ∽ 2 hrs (intermittent)

Auroral ionosphere: Auroral electrojet

auroral electrojet

	Westward jet	Eastward jet
sense of the emf	Equatorward	poleward
emf	up to 60 v/km	20 v/km
current intensity	up to 3×10^6 amp	$<10^6$ amp
magnetic disturbing force at ground level	up to 1500 γ	< 500 γ

electron density in the aurora

diffuse aurora	up to 5×10^5/cm³
active form	up to 7×10^7/cm³

conductivity of the ionosphere
up to 1.2×10^{13} esu

emf along the neutral line

10^{-5} v/cm at about 6 Earth radii.

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[a] On the basis of geomagnetic evidence, we think that the stream may at times contain protons of energy 500 kev or more confined by transported magnetic fields, perhaps tangled.

[b] Arnold et al. (15) observed a flux 10^7/cm² sec of 50 kev electrons in a solar stream.

[c] Possibly this may attain 1000/cm³.

[d] The distance from Earth's center; unit: $a = 6380$ km.

[e] Calculated using the image dipole approximation.

[f] The ratio of velocity along to that perpendicular to the lines of force in the equatorial plane is assumed to be about 30.

[g] Time for one complete oscillation between the two mirror points.

[h] The auroral zone is located between 65 and 70 deg *gm* latitude. More than 5 auroral curtains are often seen simultaneously in the belt.

[i] The curtain structure of auroras often appears there during great magnetic storms.

[j] Flux in the aurora: to obtain the corresponding flux at 6 Earth radii in the equatorial plane multiply the given number by 2.5×10^{-2}.

[k] The material in parentheses shows the corresponding thickness in the equatorial plane.

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Heat Sink Strand Bomb for Determining Ballistic Properties of Solid Propellants

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A method is presented that allows quick and economical determination of certain ballistic parameters of solid propellants. Various data are presented comparing the results from the new heat sink method, regular Crawford bomb and motor firings. These results indicate that the new method is accurate and reproducible.

THE CRAWFORD bomb (1)[4] is a well-standardized device for measuring burning rates of propellants at various pressures. It is widely used as a means of controlling manufacturer products and as a research tool. The apparatus is most convenient for the measurement of burning rate at ambient temperatures and over a range of pressures. For advanced research and production control, the measurement of temperature coefficient of burning rate at constant pressure and at constant K_n is needed. The Crawford bomb has proved less versatile for these measurements, since accurate equilibration of the test strand with the bomb immersed in a bath of the required temperature is slow and inconvenient. As a result, relatively little research data have been gathered in this field.

Through research[5] a new apparatus has been developed and used for the measurement of temperature coefficient at constant pressure. This apparatus uses a conventional Crawford bomb as developed by Crawford and his co-workers (1) from the early apparatus of Muraour (2). Our apparatus includes a massive internal heat sink to maintain strand temperature without chilling or heating the entire apparatus. This heat sink bomb has proved accurate and reliable, and it has reduced the cost and time needed to obtain data on temperature coefficient, burning rate and pressure exponent over wide temperature ranges.

Existent Apparatus

The universally used type of Crawford strand bomb evaluates the linear burning rate of small propellant strands and involves the determination of time intervals between the burning out of wires embedded at predetermined locations in the strand. Burning rates are obtained at different pressures, which are kept constant by connecting the bomb with a nitrogen regulatory system. The closed bomb is similar (3), except that the pressure above a certain minimum amount is determined by the rate of gas evolution from the burning of the propellant itself.

The temperatures of this type of bomb may be controlled by having heating and/or cooling coils in the bomb itself (4,6) or by having the entire burning apparatus immersed in a temperature bath. A variation of this method is the immersion of the strand itself in a liquid which acts as a restrictor as well as a temperature control (5). These methods are time-consuming with regard to changing temperature and costly with respect to the apparatus necessary for this change; they involve various other inconveniences as well.

Another method to determine temperature dependent ballistic properties utilizes rocket motor firings, in which equal grains are burned at various temperatures. It is often difficult to choose the correct nozzle to give a desired pressure level, and rocket tests are expensive.

Development of the Heat Sink Bomb

It was conceived that a portable heat sink composed of a large piece of metal in which a strand could be conditioned and burned might keep a constant temperature without tempera-

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[4] Numbers in parentheses indicate References at end of paper.

[5] Funded by the Amoco Chemicals Corp., Whiting, Ind.