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SOLAR INFLUENCES ON GEOMAGNETIC AND RELATED PHENOMENA

E. H. Vestine

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ABSTRACT

A discussion of the geomagnetic effects of streams of electromagnetic and particular radiation from the sun. The interplay of forces between the geomagnetic field and solar streams is outlined; and the theoretical relationship between these, the solar storms, the trapped Van Allen radiations, the polar aurora, and geomagnetic field distortion are presented.

CONTENTS

SOLAR INFLUENCES ON GEOMAGNETIC AND RELATED PHENOMENA

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Introduction. — The geomagnetic field undergoes changes with time that are closely linked to time changes in solar phenomena. Bartels has shown that the correlation of sunspots with the annual average terrestrial equatorial changes in geomagnetic field, indicated by the solar daily magnetic variation, is as high as 0.99 (Bartels, 1946). This is so high that it is believed that annual average values of certain fluctuations in solar wave radiation are well monitored by measuring geomagnetic field changes on the surface of the earth. The physical connection seems to be that the geomagnetic field changes are due to electric currents flowing in the ionosphere; these currents are produced partly as a result of dynamo action of solar-driven upper-air winds. As is also well known, other aspects such as ion amount and temperature of the ionospheric regions are affected by solar wave radiation (Chapman and Bartels, 1940).

It is found that certain transient geomagnetic changes and auroral displays in the polar regions seem linked to solar corpuscular radiation. This is clear from inspection of K-measures of magnetic disturbances of Fig. 1, which, when more intense, depend on sunspot number. The physical connection is thought of as involving solar proton streams propagated from sun to earth in about a day or so, but many of the actual features of such streams and their effects are obscure. These streams may already have been detected through the use of space probes. Thus preliminary findings on the Pioneer V solar probe have shown that magnetic fields appeared in space millions of miles from the earth, which later may have traveled to the earth, these fields possibly being locked within a moving stream of solar protons. This suggests that solar streams of particles transported a magnetic field, and that these streams would in turn interact with the outer geomagnetic field (Coleman, Sonett, Judge, and Smith, 1960). The effect of such interaction is not known, but compression of the geomagnetic field into a space 6 to 15 earth radii in the region of initial contact has been suggested (Chapman and Bartels, 1940; Dessler and Parker, 1959; Nagata et al, 1960; Beard, 1960).

Entry of Solar Particles into Geomagnetic Field. — It is known that high-energy solar protons of energies ranging up to those of cosmic rays readily penetrate the geomagnetic field, even to ground level in the case of cosmic rays. Other high-energy solar protons produce high absorption of radio waves in polar regions due to the excess of absorbing electrons created within the low ionosphere (Bailey, 1957; Leinbach and Reid, 1959). It is also known from rocket measurements of electron impacts during auroral displays that low-energy particles such as 6-kev electrons are preponderant near the E-region. These electrons are presumedly dumped from the Van Allen radiation belts (Van Allen and Frank, 1959). They are thought to be generated indirectly by streams of solar protons, or by the effect of solar proton streams upon plasma within the geomagnetic field (Dessler and Karplus, 1960). Some of these high-energy solar protons are, of course, trapped in the outer Van Allen radiation belts following solar flares, but in addition it has been suggested that low-energy solar protons also diffuse into the Van Allen region from incident solar streams (Nagata et al, 1960; and others).

Matsura and Nagata have recently estimated that unmagnetized solar streams may be able to penetrate the distorted geomagnetic field (Nagata, et al, 1960). In order that diffusion occur, it is supposed that the boundary between the solar stream and geomagnetic field includes ionized clouds of average cross section about 1000 km, enduring for about 10 seconds, enclosing irregular magnetic fields. They then find that some of the protons and electrons will drift in the direction perpendicular to that of the crossed magnetic field and field gradient. In 10^4 seconds, enough particles may enter the geomagnetic field to contribute to large geomagnetic field changes known as magnetic storms, enduring for several days.

They did not consider a magnetized solar stream in their study. It may be noted, however, that such a magnetized solar stream may also permit particles to drift down to the Van Allen radiation belts, by the same process. Rough estimates made by the writer suggest a similar efficiency of injection. Finally, as Bennett and Hulburt have suggested, there may be more concentrated segments of solar proton streams directly entering the upper atmosphere mainly on the night side of the earth (Bennett, 1958). The Bennett—Hulburt beams apparently were not noted by Pioneer V, so either they do not exist continually or were missed by Pioneer V particle counters. It may also be remarked that the irregularly magnetized clouds in outer reaches of the Van Allen belts are only conjectural, though some magnetic field roughness there has been noted by several space probes.

Consequently aurora and magnetic disturbances probably are a result of the interaction of solar streams with the geomagnetically trapped radiation of the Van Allen regions (Van Allen and Frank, 1959). This trapping may be rather transitory in character, as well as long continued as in the case of the usual Van Allen radiation. In order that the aurora and polar electrojets be produced, some of the particles probably require increases in energy (Chamberlain, Kern, and Vestine, 1960).

The way in which such radiation is dumped to form aurora and polar magnetic disturbances is not yet known. One possibility is that since the parts of the Van Allen radiation belts mirroring in high latitudes are not stable, fluted groupings of Van Allen radiation will form, given a sufficient length of time. Within these groupings transient electric fields transverse to the lines of geomagnetic force within the atmosphere should grow exponentially with the time, tending to drive segments of geomagnetically trapped charged particles polewards (Kern and Vestine, 1960). The tendency to instability may be greater on the night side where the lines of force may be stretched and the field weakened, in comparison with the day side of the earth, where compression of the geomagnetic field by the solar stream may be greater. It is possible that the flutes in the radiation belt which are created, are further affected and shaped by magnetic and electric fields (Kern and Vestine, 1961; Vestine, 1960). If a pinch-type effect is possible, penetration to auroral levels may arise, with formation of aurora and electrojets of current flowing in the E-region of the ionosphere. This is because of the diamagnetic action of any excess of electrons, say, present in the radiation segment or flute, tending to lower the radiation mirror point slightly, and perhaps facilitating the dumping of the radiation into the low ionosphere;

in addition a small component of any electric field present, if dumped along the geomagnetic field, would be more likely to be of importance in achieving significant dumping. In fact, if the solar stream distorts the geomagnetic field on the night side as suggested by Kern, electrojets driven by Hall currents may form (Kern, 1961). At the present time attempts are being made to calculate such magnetic gradients, which if directed away from the sun on the dawn and afternoon sides of the earth, should afford separated charge aggregates, which if they can be dumped into the ionosphere may provide an electric driving force for the polar electrojets. These electric forces will in turn tend to interact with the Van Allen radiation belts, and any longitudinal electric fields occasioned by compression or distension of the geomagnetic field will be likely to cause meridional drift of trapped Van Allen radiation. These various possible effects may be borne in mind while considering the various radiation shells. The latter will next be examined in more detail by use of a 48-term spherical harmonic expansion for the geomagnetic field. This material may be found useful in estimating the perturbations of the Van Allen belts caused by solar proton streams. In this work, the magnetic field of particles moving in the radiation shells is neglected, but it will be considered in a later investigation. Also defined is the shell connecting the northern and southern average auroral zones. Near this shell, important transient effects in the radiation belts are noted. Some of these effects are attributed to the electric fields of the polar electrojets, and therefore ultimately to solar streams. The contribution to the injection of radiation into the outer levels of the Van Allen region, due to the electric fields of the polar electrojets, is suggested.

An attempt is made to assess the importance of this contribution using estimates of electric fields derived from known interactions of the electrojets with the F-region of the ionosphere.

Surfaces of Particle Flow in Van Allen Regions. — The existence of radiation in belts about a magnetized sphere was demonstrated in the laboratory by Birkeland (1908, 1913), but not explained, and no doubt gave rise to the concept of a ring current encircling the earth at a distance of a few earth radii. The spiral motions and reflection of charged particles were computed mathematically by Störmer (1907). The drift of such spiralling particles in a magnetic field gradient seems to have first been discussed by Gunn (1929). The modern development of these ideas with important extensions is due to Alfvén (1953) and on the experimental side by Bennett (1958) and others. The application of some of these ideas in the theory of magnetic storms was considered by Bennett, but in more detail by Singer (1957), who considered that low-energy particles might produce magnetic storms. The discovery that particles of even quite high energy existed in large numbers in trapped condition about the earth was soon thereafter made by Van Allen and his co-workers (Van Allen, Ludwig, Ray, and McIlwain, 1958). The Argus experiment proposed by Christofilos (1959) clarified and demonstrated these ideas by creating an artificial radiation shell by means of a small atomic explosion. It was also indicated that integral invariants of the particle motion should describe the surface within the geomagnetic field defining the center of a region within which a charged particle is constrained to move (Northrup and Teller, 1960).

These surfaces are here shown in Fig. 2, the surfaces being selected by the intersections of the orbit of the probe Pioneer III with surfaces on which the radiation counts were 10,000/sec or 10/sec (Van Allen and Frank, 1959). The surfaces of Fig. 2 relate to motion, not to flux density, since the latter depends also upon the total magnetic field F (Ray, 1960; Northrup and Teller, 1960). The outermost curves are intended to terminate at the theoretical auroral zones. Each shell (shown extending to ground level in Fig. 3) actually may be regarded as terminating at a surface F = constant, a mirror point for those particles oscillating between the northern and southern hemispheres while drifting around the earth within or near the shell.

Inspection of the upper surface passing through point 2 in the inner Van Allen radiation belt reveals that, near longitudes 160W or E, the shell is at about 980 km higher elevation than near 40°E.

Figure 3 shows this result in another way and the intersections of the shells of Fig. 2 with the earth's equatorial plane. The results as before are based on the 48-coefficient spherical harmonic analysis for 1955 (Finch and Leaton, 1957). The actual maximum range in height was not obtained, but the inner shell in the figure was calculated to be at height 3300 km above latitude 2°S, longitude 160°E and 2318 km above latitude 1°N, longitude 31°E, which gives an indication of the range. The heights of the mirror point F = 0.5 cgs for the outer shell are indicated in Fig. 4, together with maximum heights and field values of the shell near the equator.

The geomagnetic annual and sunspot variations: Figure 5 shows the latitude distribution of the daily averages of geomagnetic disturbance for the 5 selected internationally disturbed days each month of 1922-33, (Vestine, Lange, Laporte, and Scott, 1947). The geomagnetic east component shows scarcely any variation with latitude between the northern and southern auroral zones. This is compatible with motion of particles along the surfaces or shells of Fig. 3, approximately in the direction perpendicular to both the gradient of the geomagnetic field and the field itself. This adds credence to the view rapidly becoming established that averages of disturbances over periods of a day or more arise from drifting particles in the radiation belts.

Another feature is the added bulge in the geomagnetic north component extending for some distance to the north or south of the geomagnetic equator. This is of course likely to be due to the added average field of particles drifting in the high-energy (inner) Van Allen radiation belt.

The total current flowing from east to west could of course be easily estimated, for instance, by supposing the current flow in the outer and inner Van Allen radiation belts replaced by a thin shell near the maximum radiation density of each Van Allen region measured near the equatorial plane. If the ratios of the magnetic field contributions by each shell are taken to be about 3 to 25, say, as seems reasonable from inspection of the data of Fig. 5, one-eighth of the equatorial part of the disturbance field averaged around parallels of latitude arises from the inner Van Allen radiation belt. This result seems to be in good qualitative agreement with Van Allen's results based on Pioneer III and IV, and should be checked when the average complete spectrum of energies becomes available.

The auroral-zone effects are known to be due to sources near the E-region in the case of the polar electrojets, though a minor contribution to the electrojets may arise, as Dessler and Parker (1959) suggest, from the mirroring of particles from the radiation belt. They also point out that there is a contribution from the interhemispherical motion of the trapped particles, and provide estimates of this contribution.

The Electric Field of the Polar Electrojet. -- In auroral regions, northern and southern, intensifications of the geomagnetic field of 500 to 1000 gammas (1 gamma = 10^{-5} cgs-unit) occur. These are called magnetic bays and appear almost nightly, often in sequences of several nights, above the same locality, beginning at about the same hour (Chapman and Bartels, 1940). They last from about one to five hours. They are due to concentrated electrojets of current within or near the E-region of the ionosphere at a height of about 100 km. The total current flowing in the electrojet is estimated to be about 500,000 amperes, but may rise to values in excess of 1,000,000 amperes (Vestine, Lange, Laporte, and Scott, 1947). The actual current cross-section has not yet been measured, but may be several hundred kilometers wide and perhaps 50 km thick; the distribution of current might also be that for auroral arcs. The electric conductivity of the region is normally augmented by aurora. If the conductivity is taken to be about 10^2 times normal, electric potentials of less than one-tenth mv/cm directed from north to south should drive the early morning electrojet. This potential arises from dynamic effects associated with the aurora, and perhaps also from upper-air winds.

Obayashi (1959) has recently summarized results of his own and other studies of the influence of the polar electrojets and other features of magnetic storms upon the ionosphere. Though certain features of the interrelationship between the phenomena are obscure, it seems likely that the electric field of the polar electrojets raises or lowers the F-region of the ionosphere (Martyn, 1953).

The effect of the electrojet on the F-region varies with the intensity of magnetic disturbance and may be great enough to blow the F-region from the upper atmosphere within an hour (Berkner and Seaton, 1940). Ordinarily there are only modest changes in height with a rise in the F-region of some tens of kilometers. A rise in height, or lowering of the critical frequency f_oF_2, is common on the forenoon side of the earth and may be accompanied by a lesser transient depression in height at night.

The F-region may rise or fall in response to the motor effect of electric currents. The F-region may also move in response to a crossed electric and magnetic field. If its velocity is v, this may be regarded as the driven velocity of ions and electrons (Martyn, 1953). If for the moment only the electrons are regarded, the current i is given by

$$\underline{i} = Ne\underline{v} = \sigma_2 \, \underline{h} \times \underline{E}/H \qquad (1)$$

where $\underline{i}$ is the current, N the charge density of electrons (neglecting positive charges for the moment, since we are interested mainly in motion of electrons only), e the electronic charge, and $\underline{v}$ the velocity across the field lines. Also σ_2 is the electric Hall conductivity, $\underline{h}$ a unit vector in the direction of the magnetic field $\underline{H}$, and $\underline{E}$ the electric field.

Since

$$\sigma_2 = \frac{Ne^2}{m\,\nu}\;\frac{\nu\,w}{\nu^2 + w^2} \qquad (2)$$

where ν = collisional frequency and w the spiral frequency, He/m. When $w > \nu$, as is true is the upper ionosphere and above, then very nearly

$$\sigma_2 \sim NeE/H \qquad (3)$$

and from (1) $Nev = NeE/H$ or

$$v = E/H \sim 3ER^3 \qquad (4)$$

since $H \sim 0.3/R^3$ in low latitudes, and is very nearly the same for ions.

Because of the decrease in H with height, v increases rapidly as R^3, while E is reduced with height because of electromagnetic induction. If H = 0.5 and vt = 40 km where t is 4,000 sec, $E = Hv = 0.5 \times 40 \times 10^5/2000 = 10^3$ emu $= 10^{-5}$ volts/cm. Above R is distance from the earth's center to the F-region measured in earth radii. Of course, even if a very feeble current flows across the field, a noticeable motor effect may occur and even dominate in determining the motion of the electrons, whether ambient as in the F-region or in the form of Van Allen radiation within the exosphere. If the upward penetration of the electrojet fields including those closing the electrojet circuits were calculated, which appears, unfortunately, to be a matter of considerable difficulty, more precise estimates could be made of the charges in the radiation belt caused by the polar electrojets. In this connection, it may be noted that electrojets may closely simulate an ideal electric doublet, or appear as the superposition of many such doublets distributed along the auroral zone. From data on transmission of geomagnetic fluctuations in the ionosphere theoretically estimated by Piddington, it is clear that electrojets of short duration, say an hour or less, cannot provide an electromagnetic signal penetrating very far into the ionosphere, so the outer Van Allen region should not be affected (Piddington, 1959). It may also be that additional electric fields are present, as Alfven has supposed (Alfvén, 1950). A sharply defined electrojet may also, under certain conditions, be associated spatially with auroral rays, within which at least a part of the electrojet actually flows. The electrojet and auroral display may then move south together (Heppner, 1954). If such a jet is formed of down-coming solar particles, some of which are reflected, the latter may be able to enter a trapped condition in the outer Van Allen radiation belt. Since on relatively quiet days the auroral zone is farther poleward, a greater radial extent of the outer Van Allen region during quiet periods might be expected. There appear to be some reasons for believing that this may be the case (Van Allen, McIlwain, and Ludwig, 1959; Jastrow, 1959; Vestine, 1960).

Other Effects of Electric Fields Originating in the Polar Ionosphere.— It has been noted that with the aid of a few satellite radiation measurements, and calculations of the geomagnetic field above the ground, the approximate geometry of various radiation shells at any given time can be inferred, using the theory of drifting trapped radiation. This expectation is justified for the inner Van Allen belt, within which the geomagnetic field is of adequate intensity to maintain high stability. This may also be true for much of the outer belt, but there is a much greater chance of disturbing effects, such as those due to solar-stream fluctuations because the geomagnetic field is less intense at high equatorial elevations. The latter disturbing effects arise also from the propagation of electromagnetic effects upward from the low ionosphere, or downward from the hypothetical boundary between the solar stream and the geomagnetic field.

It is known from geomagnetism that transverse electric fields occur within the ionosphere. These electric fields may grow exponentially with time at a rate such that an e-fold increase occurs in the time

$$t = \sigma_1 AH/4L p\nu_d \qquad (5)$$

where σ_1 = the transverse electric conductivity, A the ionospheric electrojet-current cross-section, H the magnetic field, L the length of field lines between mirror points, p the charge density, and ν_d the drift velocity (Kern and Vestine, 1960). An atmospheric wind-produced irregularity in electric field, for example, may possibly also initiate flutes within the terminating region of a given radiation shell. The effect is mainly of shift of a segment of the base of the shell, as a flute, along its entire interhemispherical length into an adjacent shell. This may be one possible cause of the remarkable number if irregularities in radiation counts noted by earth satellite within the outer radiation belt. At night, when the transverse conductivity σ_1 is less, the time constant for growth of flutes is shorter. Some of these problems have been otherwise treated recently by others (Dungey, 1959; Gold, 1959; Parker, 1960).

It may be remarked that longitudinal gradients in the geomagnetic field near the boundary between the solar stream and the geomagnetic field and due to fluctuations in the compressive and distorting influence of the solar streams will cause the shells of electrons or protons in the radiation belts to drift in a direction perpendicular to both the geomagnetic field and the magnetic field gradient. This drift is opposite for protons and electrons (Kern, private communication). It seems likely to be an important reason for migration of charge aggregations in the outer Van Allen radiation belt, or even into the gap between the outer and inner belts. Within the latter region, differences in charge distribution within the outer and inner radiation belts may arise from longitudinal magnetic field gradients. It would be of high interest to know if there may arise a resultant component of electric field directed along the geo-magnetic field which would cause dumping of trapped or other particles. This mechanism may also contribute to the gap between outer and inner belts; qualitatively speaking, the protons would respond to the east--west longitudinal gradient by drifting outwards from the earth in the outer radiation belt and some electrons would drift downwards above the equator.

Oscillations in the direction of the longitudinal magnetic gradient in the equatorial plane would of course give rise to oscillatory effects often noted in the polar electrojets flowing in auroral regions of the ionosphere. If these theories are correct, a knowledge of the polar disturbance field should permit estimates of the distortion of the geo-magnetic field in nearby space from ground-based observations. There is need for a quantitative discussion in order to assess the importance of this effect, as well as of the elctric acceleration responsible for the dumping of auroral particles; the latter will also depend upon and affect the spectrum of energies present and the numbers of particles in trapped condition.

Summary. - Several shells along which a particle trapped in the Van Allen radiation belts must move are defined by means of calculations of the geomagnetic field and integral invariants of the particle motion

for 1955.0, neglecting the influence of ring-current magnetic fields. Such a shell passing through the inner Van Allen radiation belt is found to be at vertical height 2320 km, at latitude 1°N, longitude 31°E. The height is 3300 km at latitude 2°S, longitude 160°E. The height of the 0.5-gauss mirror points for particles approaching the auroral zones in various longitudes is indicated.

The polar electrojets may arise from distortions of the geomagnetic field by solar streams, providing a dumping of auroral particles trapped temporarily and accelerated within outer reaches of the Van Allen radiation belt or region; longitudinal magnetic field gradients should separate proton and electron shell segments. The strong nighttime electrojet should then be driven by the approximately north--south electric field of the dumped particles; the electrojet of the early evening should arise from the south--north electric field. These polar electrojets, which are located at the northern and southern auroral zones, probably in turn distort adjacent portions of the radiation belts because of the electric fields of the electrojets, but it is difficult to estimate the importance of this effect. During magnetic storms, the penetration of the electric field driving the electrojets extends as a return circuit to higher levels above the earth, since the field change is of longer duration. For the morning electrojet, the electrostatic field closing the ionospheric current circuit is likely to be from west to east within lower reaches of the belts, and should drive the radiation upwards and polewards, so that some of it may be lost into space. The electrojets are farther equatorwards during a storm, so that a wide section of the upper part of the outer radiation belt might be removed.

A more important source of electric field may arise from transient compression and rarefaction of the geomagnetic field by solar streams. This should provide a longitudinal component of electric field in the outer Van Allen region causing poleward or equatorward drift of radiation shells.

During quieter periods, the electrojets, now farther poleward, endure for so short a time (an hour or so) that penetration of their electric fields is insignificant at radiation-belt level. The general effect may be therefore summarized by remarking that in the case of minor magnetic disturbances the distribution of electrical driving forces will be mainly a two-dimensional skin effect confined to the lower ionosphere, whereas in the case of large enduring disturbances, there may be deep though feeble penetration into the Van Allen regions as well.

Longitudinal geomagnetic field gradients due to streams of solar protons will be likely to cause local distortions in the radiation belts. The transfer of charge from magnetized solar streams of 50-kev energy to the geomagnetic field seems most likely just after dawn, in the case of protons, and in the late evening for electrons, on the basis of calculations by Matsura and Nagata (1960); in this case the particle radiation in the belts will then undergo an additional drift as a whole to the east.

Quite near the electrojets, the gradients in the combined main and electrojet magnetic fields will cause complex drifts to occur in the case of downcoming beams of auroral particles. These fields may have pronounced effects in shaping auroral forms caused by the downgoing or upgoing particles spiralling in the geomagnetic field.

It is suggested that about one-eighth of the current responsible for the annual and sunspot variations in geomagnetism flows in the inner Van Allen radiation belt.

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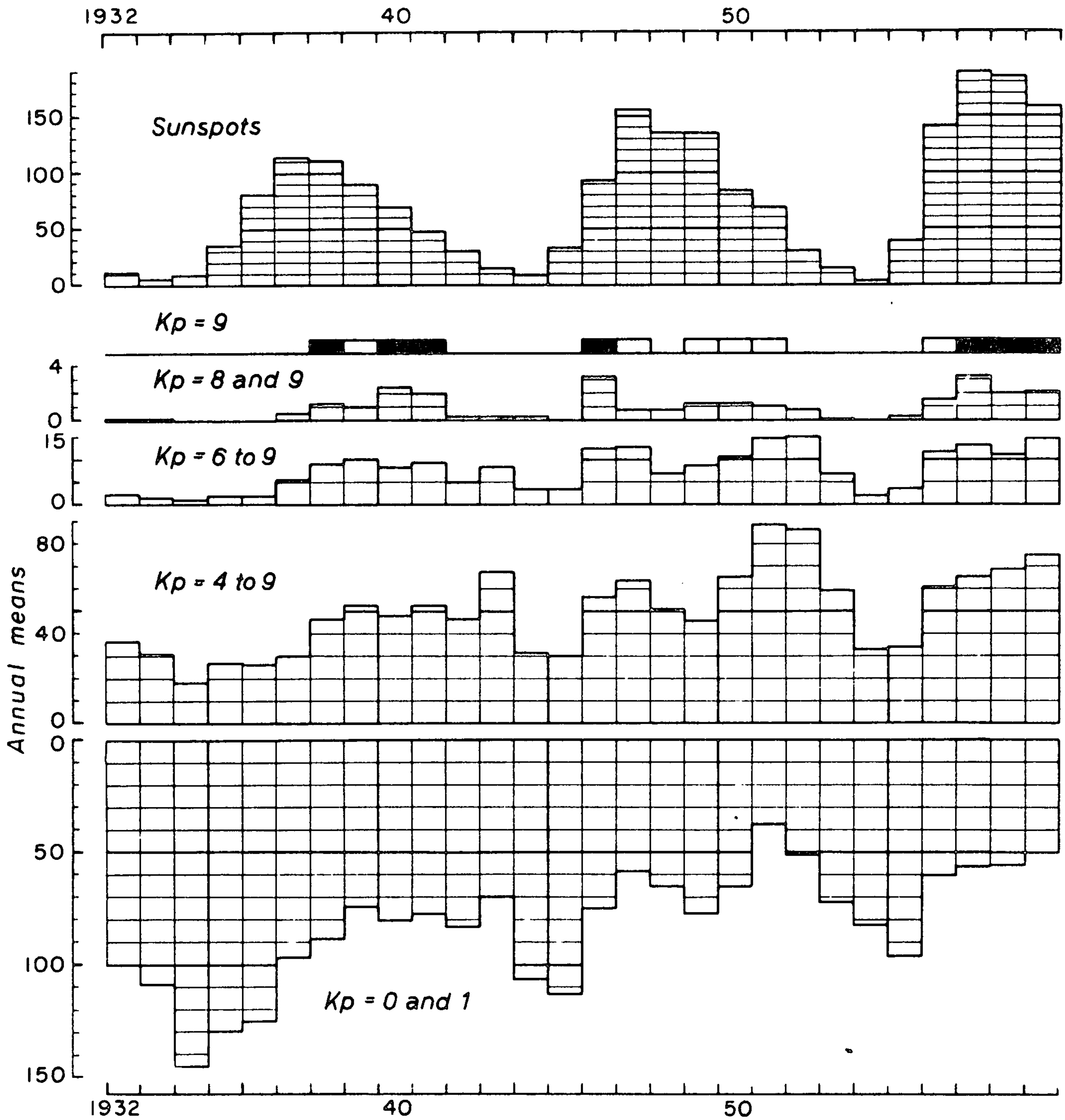

Fig. 1 -- Sunspot numbers and frequencies of range indices, annual values (after Bartels)

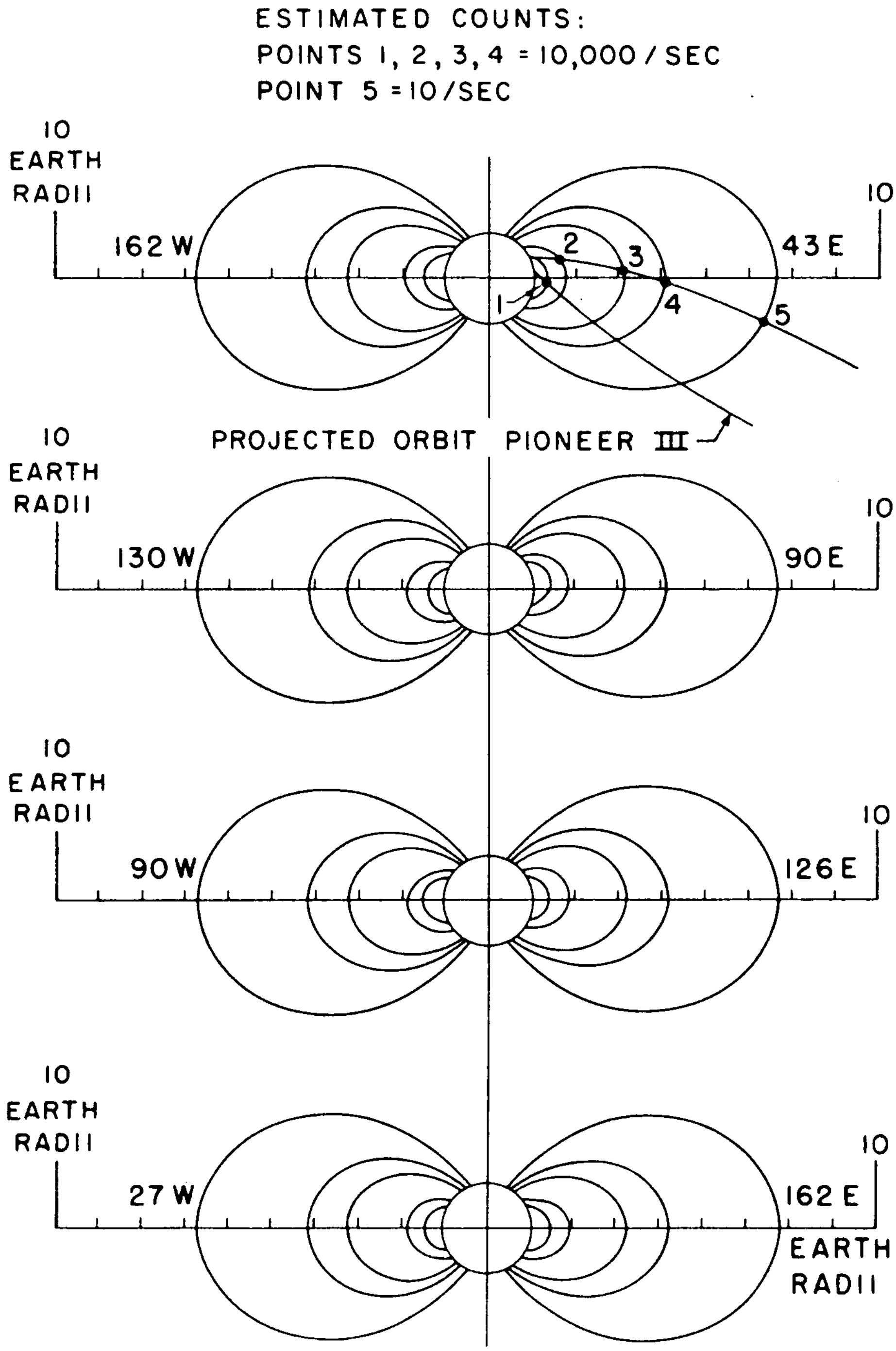

Fig. 2 — Computed projections of geomagnetic field lines on eight meridional planes

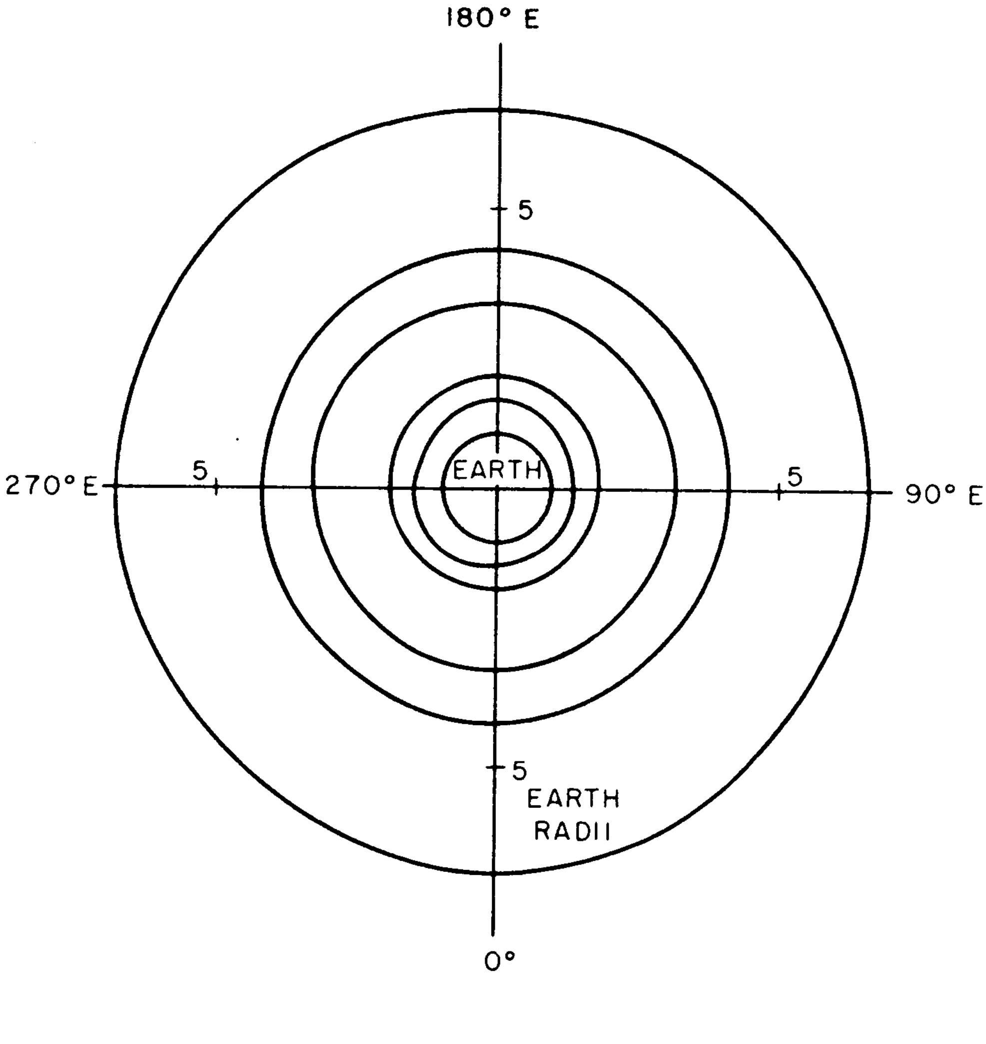

Fig. 3 — Equatorial section of drift shells for Van Allen radiation spiraling along field lines of Figure 2. Geomagnetic coordinates

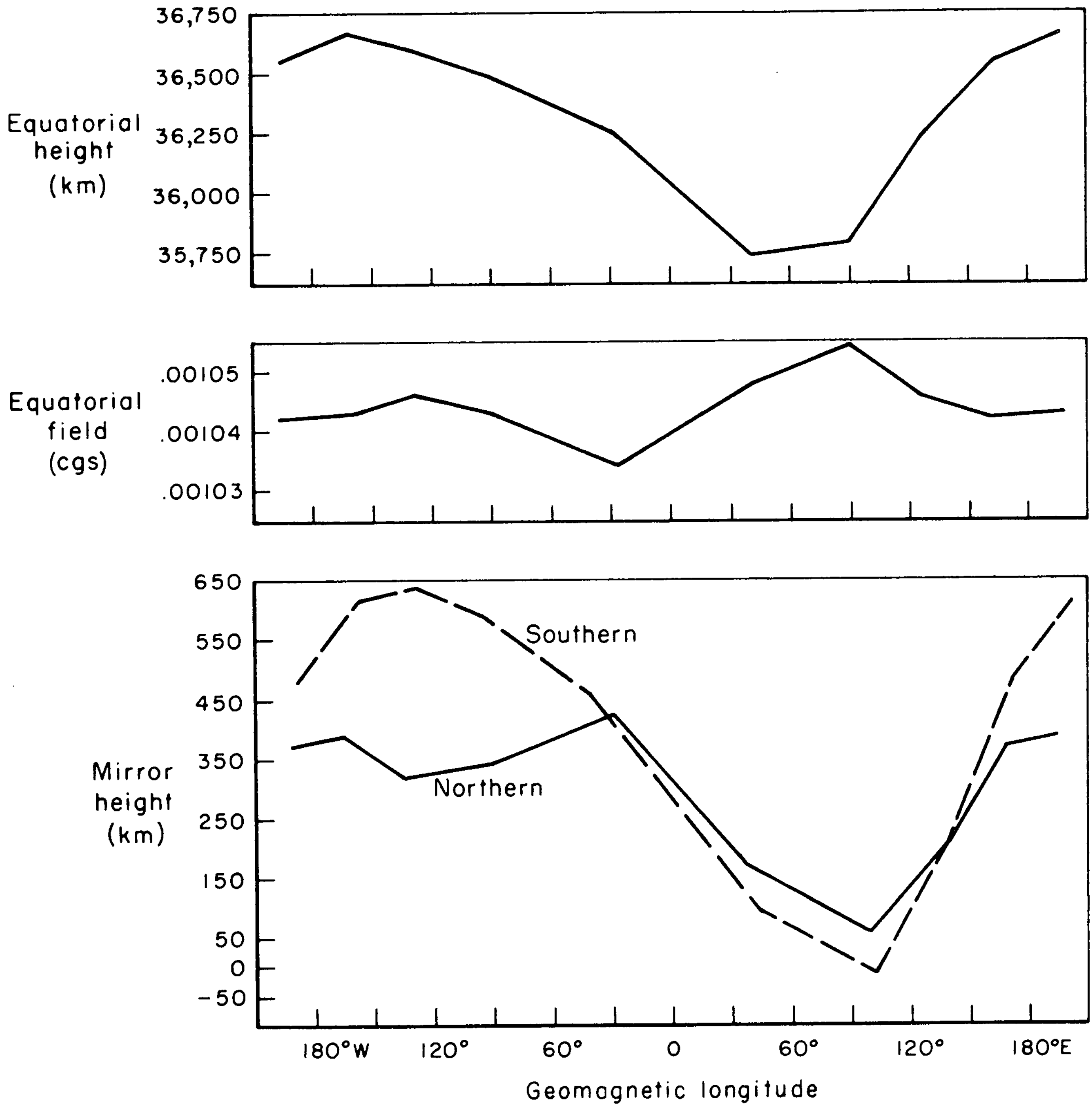

Fig. 4 — Maximum heights of lines of force at equator, field values; also corresponding high-latitude mirror heights of these lines

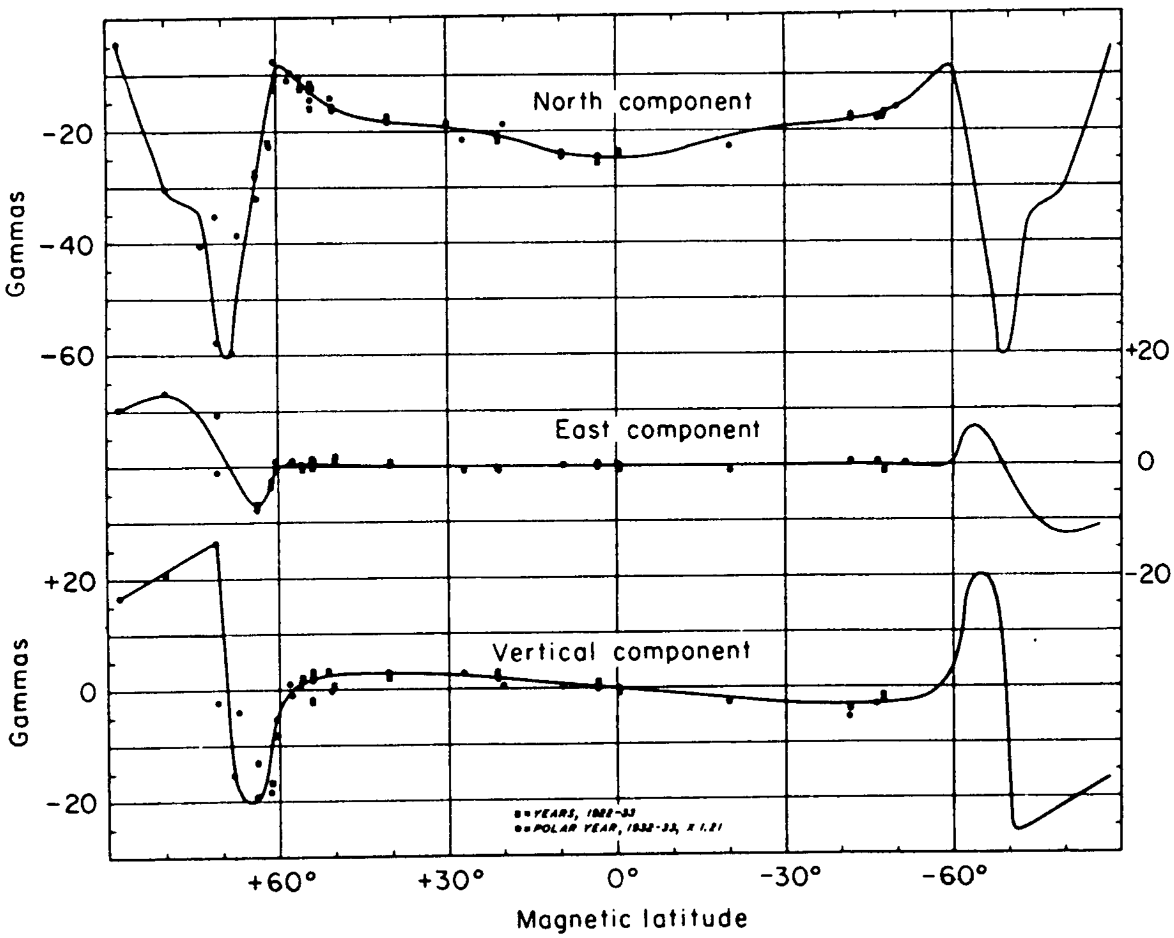

Fig. 5 — Variation with geomagnetic latitude in the daily averages of geomagnetic disturbance

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