Polar, Magnetic, Auroral, and Ionospheric Phenomena

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1. INTRODUCTION

THE present remarks concern especially thoes aspects of magnetic storms which appear to arise from atmospheric sources, though their ultimate causes may be situated beyond the atmosphere. The intense electric currents flowing in the auroral regions are described, since their substantial magnetic field contributions should be easily measurable by rocket-borne magnetometers, with related spacial features of the polar and low latitude fields measurable by polar orbiting earth satellite. The earth as a mirror machine is described, and certain theoretical treatments successfully used by physicists in the laboratory are applied.[1] It is shown that integral invariants of auroral particle motion can very successfully delineate the average auroral isochasms. Finally, there are discussed features of auroral morphology which seem explicable on the basis of stability considerations of plasma physics.

2. ELECTRIC CURRENT SYSTEMS

Although magnetic fields measured at the surface of the ground during magnetic storms can arise from many atmospheric current configurations, an electric current system flowing in the lower more electrically conducting ionosphere is considered. Figure 1 shows such a current system proposed by Chapman,[2] here indicated in two parts for an hour of a geomagnetic storm.[3] It is clear that the concentrated currents near latitude 65°N, which are estimated for a height of about 100 km, must indeed flow at about this level or below. Otherwise a very complicated and singular system would be needed to explain the geomagnetic field changes at ground level. Consequently, the two polar electrojets, an intense one directed to the west on the night side, and another one on the day side must flow near this level—a fact yet to be proved by rocket research. The equatorial part of the current flow could be explained by a broad ring current encircling the earth at a few earth radii or beyond.[4] In fact, recent rocket results by Heppner[5] and his colleagues seem to indicate a flow in this region above 2000 km or more, during several magnetic storms.

[1] R. F. Post, Revs. Modern Phys. **28**, 338 (1956).
[2] S. Chapman, Terrestrial Magnetism and Atmospheric Elec. **40**, 344 (1935).
[3] E. H. Vestine, L. Laporte, I. Lange, and W. E. Scott, Carnegie Inst. Wash. Publ. No. 580 (1947).
[4] S. Chapman and J. Bartels, *Geomagnetism* (Oxford University Press, New York, 1940), Vol. 2.
[5] J. P. Heppner, J. D. Stolarik, I. R. Shapiro, and J. C. Cain, "Project Vanguard magnetic field instrumentation and measurements," The First International Space Science Symposium, Nice, France (January, 1960).

3. AURORAL ISOCHASMS

Aurora appear most frequently and with highest intensity within two zones a few hundred km wide encircling the earth roughly near latitudes 67°N and S. The rough center of the northern auroral zone, the geomagnetic North Pole, is near Thule, in Northern Greenland. It is at the end of the geomagnetic axis of the earth given by the uniformly magnetized sphere representation of the geomagnetic field. The lines of force usually leave the Southern Hemisphere and penetrate the ground in the Northern Hemisphere. It has also long been noted that auroral rays of illumination appear aligned more or less closely to geomagnetic field lines in the upper atmosphere. Early theoretical studies (Störmer[6]) considered auroral particles spiraling down a line of geomagnetic force to a height a hundred km or so above the ground where they were reflected at a suitable magnetic field value. In the absence of collisions a particle in the Northern Hemisphere would then spiral and move along a line of force into the Southern Hemisphere where in the same way the reflection process would be repeated. This was demonstrated experimentally, though not explained by Birkeland,[7] and more recently by Bennett[8] and others. Gartlein[9] and his co-workers, using visual auroral data of the International Geophysical Year, have in fact found excellent general statistical evidence of simultaneity of aurora in the Northern and Southern Hemispheres.

Various workers, Chapman and Ferraro,[10] Alfvén,[11] Martyn,[12] Singer,[13] and Vestine,[3] have inferred that charged particles might leave a ring current distributed symmetrically about the equatorial plane to penetrate the earth's atmosphere into the auroral zones to

[6] C. Störmer, Arch. sci. phys. et nat. 140 (1907).
[7] K. Birkeland, *Norwegian Aurora Polaris Expedition*, 1902–1903, Christiania **1**, Part 1, 39 (1908); Part 2, 319 (1913).
[8] W. H. Bennett, Rev. Sci. Instr. **30**, 64 (1959).
[9] C. W. Gartlein, U. S. Visual Observations, News Letter No. 18 (Ithaca, New York, February 23, 1959).
[10] S. Chapman and V. C. A. Ferraro, Terrestrial Magnetism and Atmospheric Elec. **36**, 77, 171 (1931); **37**, 147, 421 (1932); **38**, 79 (1933); V. C. A. Ferraro, J. Geophys. Research **57**, 15 (1952).
[11] H. Alfvén, Kgl. Svenska Vetenskapsakad. Handl. **18**, 1 (1950); *Cosmical Electrodynamics* (Oxford University Press, New York, 1950); Tellus **7**, 50 (1955); **10**, 104 (1958).
[12] D. F. Martyn, Nature **167**, 92 (1951).
[13] S. F. Singer, Trans. Am. Geophys. Union **38**, 175 (1957).

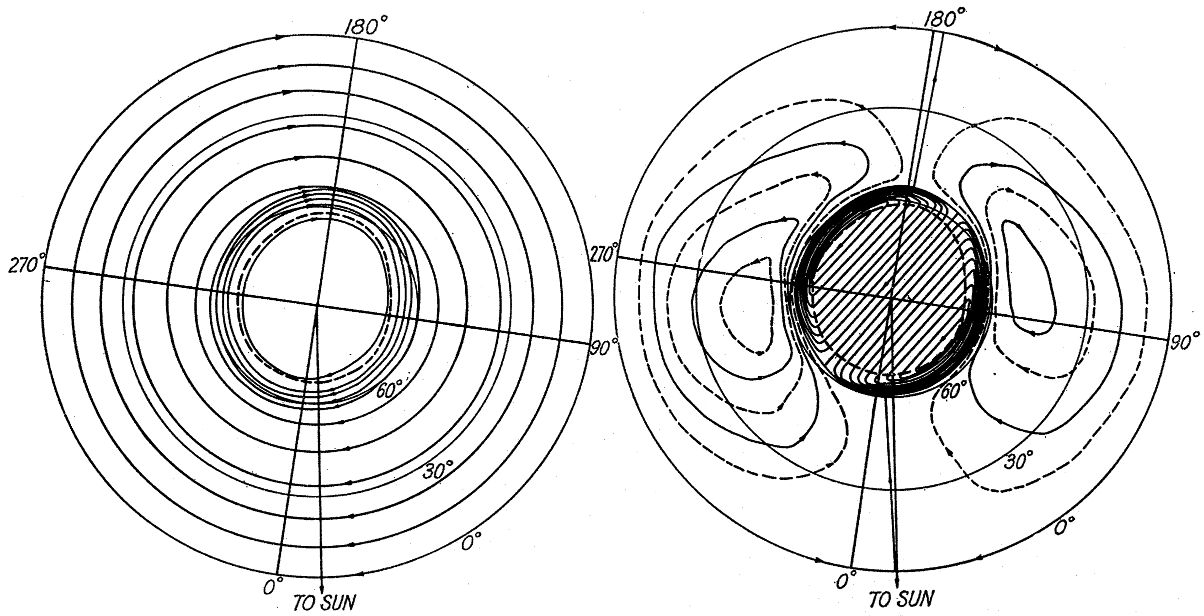

FIG. 1. Mean hourly electric current-systems of magnetic storms if confined to ionosphere, viewed from above geomagnetic North Pole (100 000-amp flow between successive current lines). (In two parts for an hour of a magnetic storm.) (a) 16^h GMT, May 1, 1933; (b) 16^h GMT, May 1, 1933. - - - =average auroral zone.

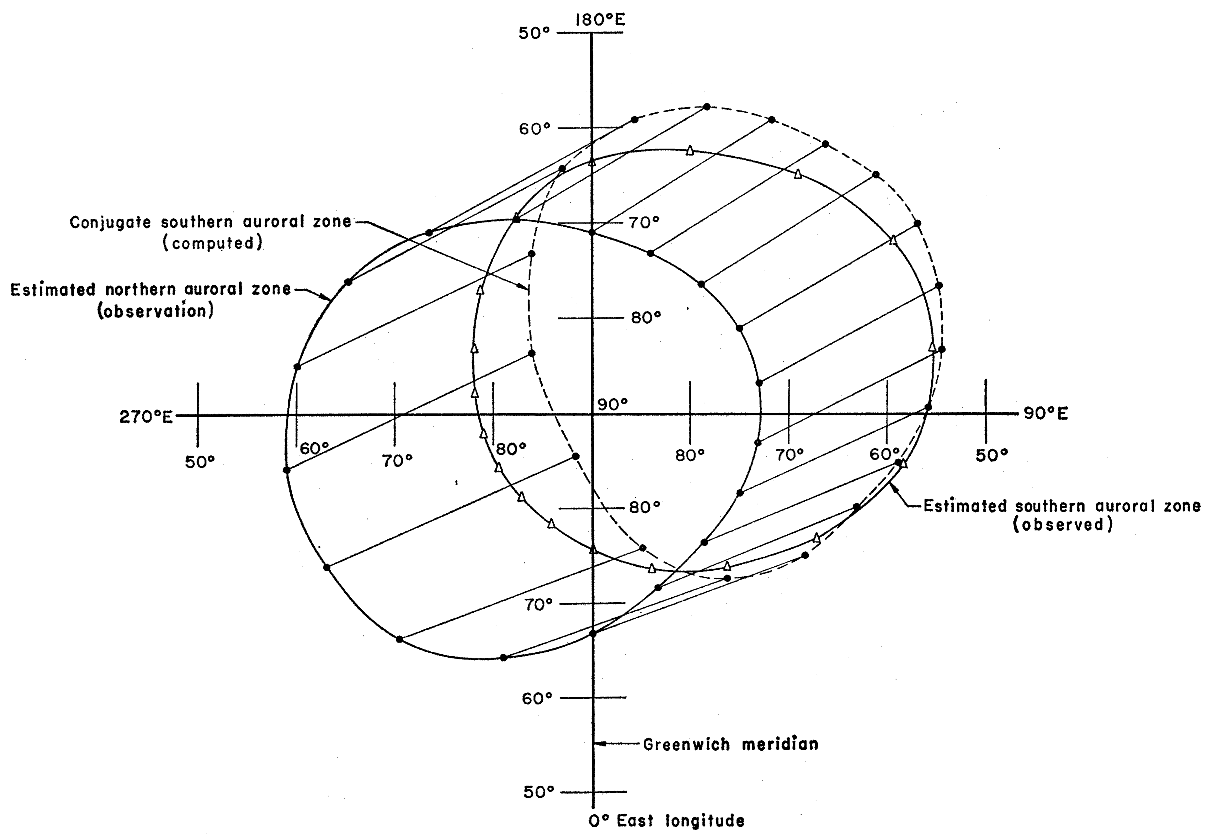

FIG. 2. Average northern and southern auroral zones as seen from above North Pole. Computations based on 48 Gauss coefficients for 1955.

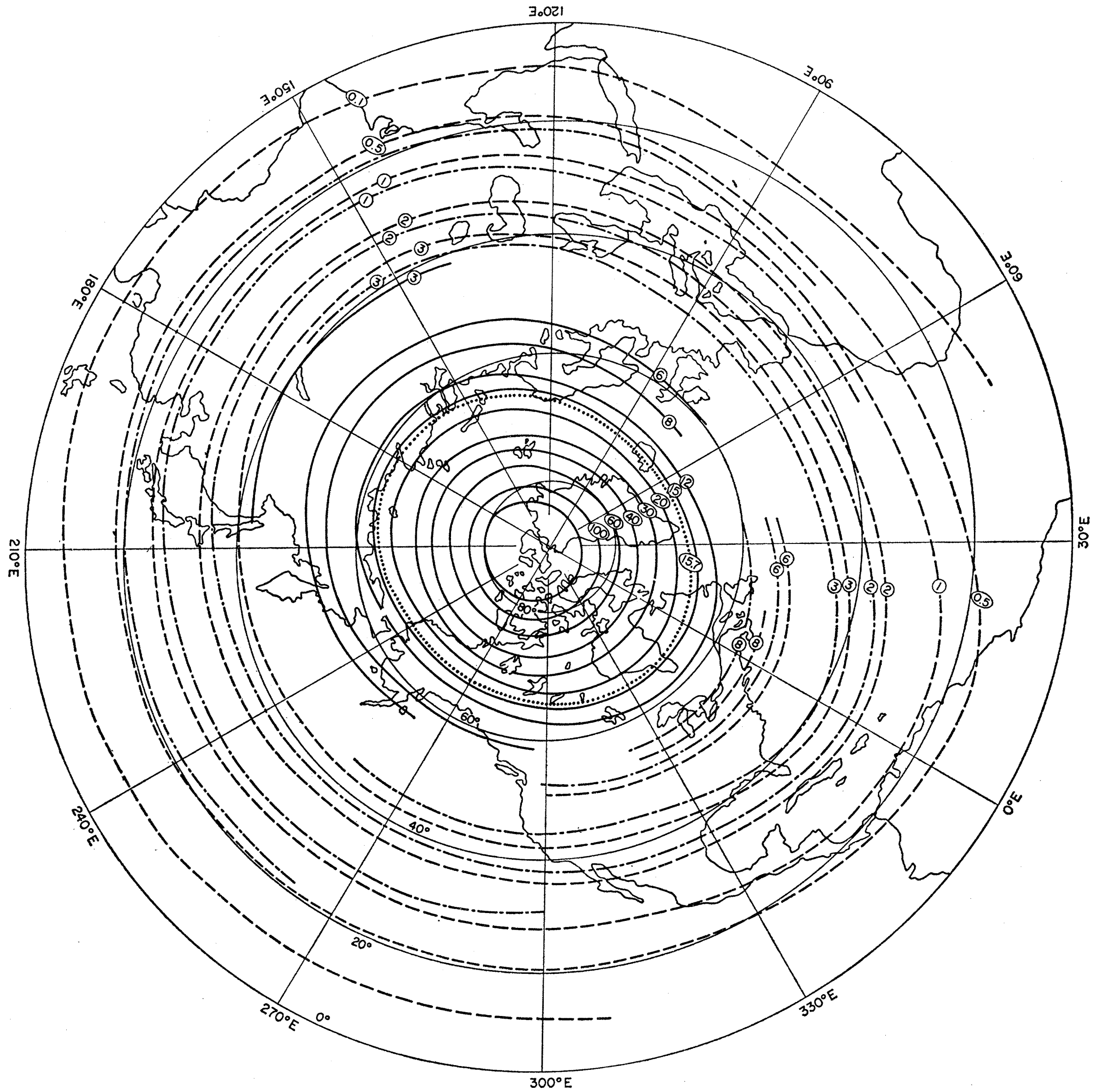

FIG. 3. Contour lines corresponding to equal integral values I, Northern Hemisphere, geomagnetic coordinates. Legend: ———, $F=0.45$ cgs; — — —, $F=0.30$ cgs; - - -, $F=0.20$ cgs; · · ·, $F=0.50$ cgs ($I=15.7$ only).

produce aurora and polar geomagnetic disturbances. If this is so, and particles leave a current ring they should then arrive at auroral levels along a specified auroral zone. The position and shape of the ring current, and the field lines intersecting it, may determine the zone of maximum auroral frequency.

4. GEOMAGNETIC LINES INTERLINKING THE AURORAL ZONES

Figure 2 shows the average northern auroral zone and its computed conjugate auroral zone in the Antarctic projected on the earth's equatorial plane, together with an estimated southern auroral zone based on most available auroral observations prior to the International Geophysical Year.[14,15] The concept of interlinkage by geomagnetic field lines of the northern isochasm of maximum auroral frequency in Northern Canada (if correctly estimated), with the isochasm in the Antarctic appears to predict an average southern auroral zone in fair accord with observation,[16] though there remains to be discussed a discrepancy of consider-

[14] E. H. Vestine, Terrestrial Magnetism and Atmospheric Elec. **49**, 77 (1944).

[15] E. H. Vestine and E. J. Snyder, Terrestrial Magnetism and Atmospheric Elec. **50**, 105 (1945).

[16] E. H. Vestine and W. L. Sibley, J. Geophys. Research **65**, 1967 (1960).

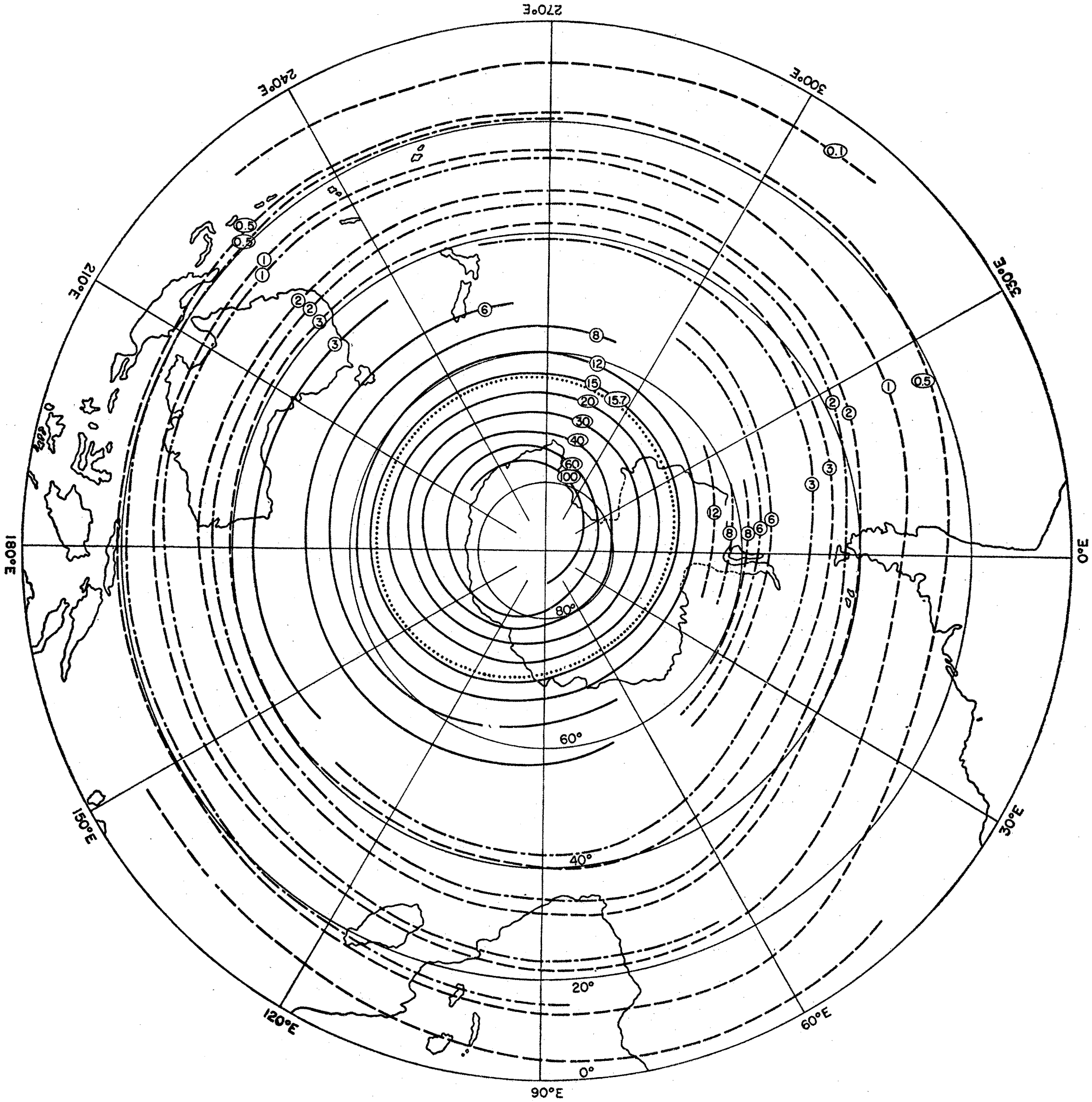

FIG. 4. Contour lines corresponding to equal integral values I, Southern Hemisphere, geomagnetic coordinates. Legend: ———, $F=0.45$ cgs; — - —, $F=0.30$ cgs; - - -, $F=0.20$ cgs; · · ·, $F=0.50$ cgs ($I=15.7$ only).

able amount between the calculated and probably observed position of the southern auroral zone near the South Pole.

In a recent study, using integral invariants of auroral particle motion, based on the theory of Rosenbluth and Longmire,[17] theoretical isochasms were derived. Discussion of this concept in relation to the Van Allen radiation belt, following a suggestion by Northrup has previously been given by Van Allen, McIlwain, and Ludwig.[18] Though injection of charged particles directly from solar streams to produce aurora may be possible, integral invariant properties can be computed, based on the concept of spiralling particles along lines of geomagnetic force, alternating in rapid succession between the Northern and Southern Hemisphers. The result is so successful in describing auroral isochasms that a temporary trapped status of the particles seems indicated. The integral invariant can be defined as

[17] M. N. Rosenbluth and C. L. Longmire, Ann. Phys. (N. Y.) **1**, 120 (1957).

[18] J. A. Van Allen, C. E. McIlwain, and G. H. Ludwig, J. Geophys. Research **64**, 877 (1959).

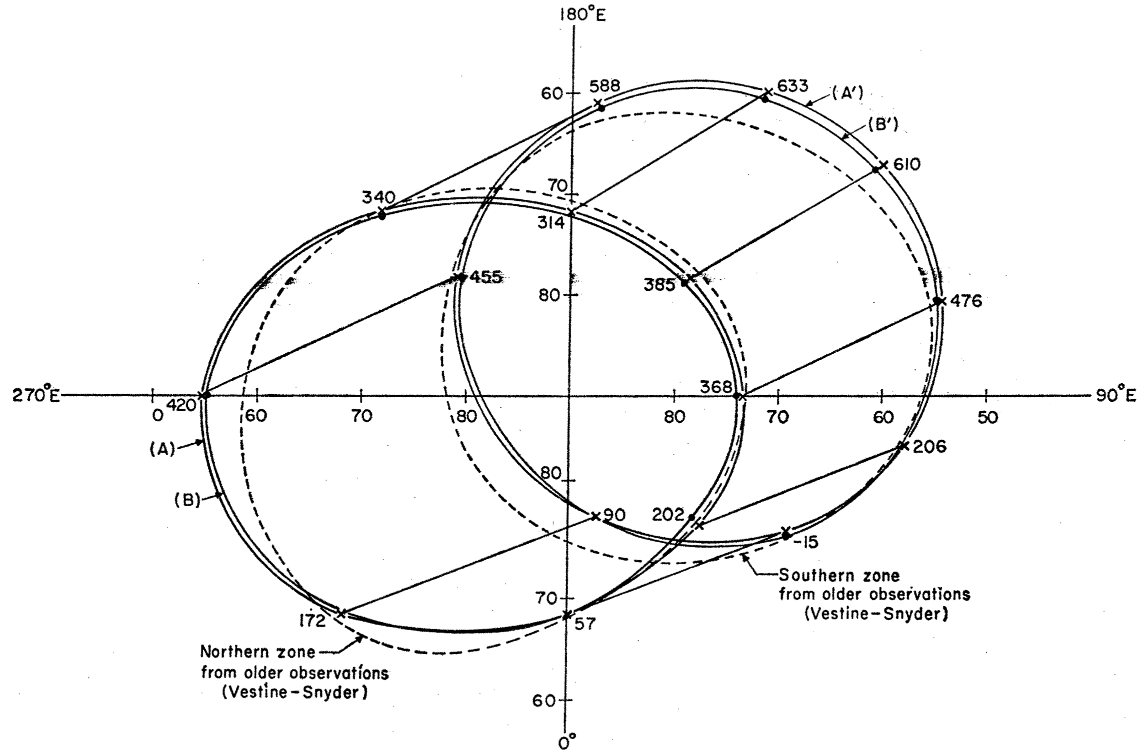

FIG. 5. (A) Curve of equal integral invariant for $I=15.7$, on surface $F=0.50$ cgs, heights in km; (B) projection of (A) along field lines to height 100 km, and corresponding southern conjugates (A′) and (B′).

given by

$$I=\frac{1}{v}\int_{m_s}^{m_n} v_1 dl, \tag{1}$$

where v is the particle velocity (practically constant between collisions), v_1 the component of v parallel to a line of force l, and m_s, m_n the mirror points for reflection of the spiraling particle in the Southern and Northern Hemispheres, respectively. If v_2 is the spiral velocity, from the invariance of magnetic moment concept $v_2^2/F=v^2/F_m=$constant, where F_m is the mirror point for the magnetic field F and $v^2=v_1^2+v_2^2$, (1) may be written

$$I=\int_{m_s}^{m_n}\left(1-\frac{F}{F_m}\right)^{\frac{1}{2}} dl. \tag{2}$$

During excursions between mirror points electrons drift eastward and protons westward, but must in so doing satisfy (2). This has recently been discussed in more detail by Northrup and Teller,[19] and by Ray.[20]

Figures 3 and 4 show contours of equal I derived for the Northern and Southern Hemispheres obtained by numerical integration of geomagnetic field values based on 48 spherical harmonic coefficients for 1955.[21] The most accurately defined curve is that for 15.7 based on detailed machine calculations. If $I=15.7$ drawn on the geomagnetic field surface $F=0.5$ gauss, is regarded as an auroral isochasm, it would apply at a time, say, of moderate geomagnetic storm or disturbance. The value $I=20$ may be more descriptive of average conditions, and agrees well with a few early comparisons of the new data for the International Geophysical Year.

Aurora ordinarily most frequently extend downwards to just above the 100-km level. The lines of force intersecting the curves $I=15.7$ in the Northern and Southern Hemispheres have accordingly been extended to the 100 km level in Figs. 5 and 6, where appropriate values F_m are indicated, or heights h above the ground to the surface $F_m=0.5$ are shown. Thus simultaneous aurora in the Northern and Southern Hemispheres are more likely in some longitudes than others. In fact, the values $h=-15$ to 100 km or so define points within areas absorbing auroral particles without sensible reflection.

5. CAUSES OF POLAR MAGNETIC, AURORAL, AND IONOSPHERIC DISTURBANCES

The problem of injection of particles from solar streams is little understood. The most attractive possibility may be that the Chapman-Ferraro solar streams provide a supply of particles by loading the geomagnetic field to capacity at the surface of contact

[19] T. G. Northrup and E. Teller, Phys. Rev. **117**, 215 (1960).
[20] E. C. Ray, *On the Theory of Protons Trapped in the Earth's Magnetic Field* (State University of Iowa, Iowa City, Iowa, 1959).
[21] H. F. Finch and B. R. Leaton, Monthly Notices Roy. Astron. Soc. Geophys. Suppl. **7**, 314 (1957).

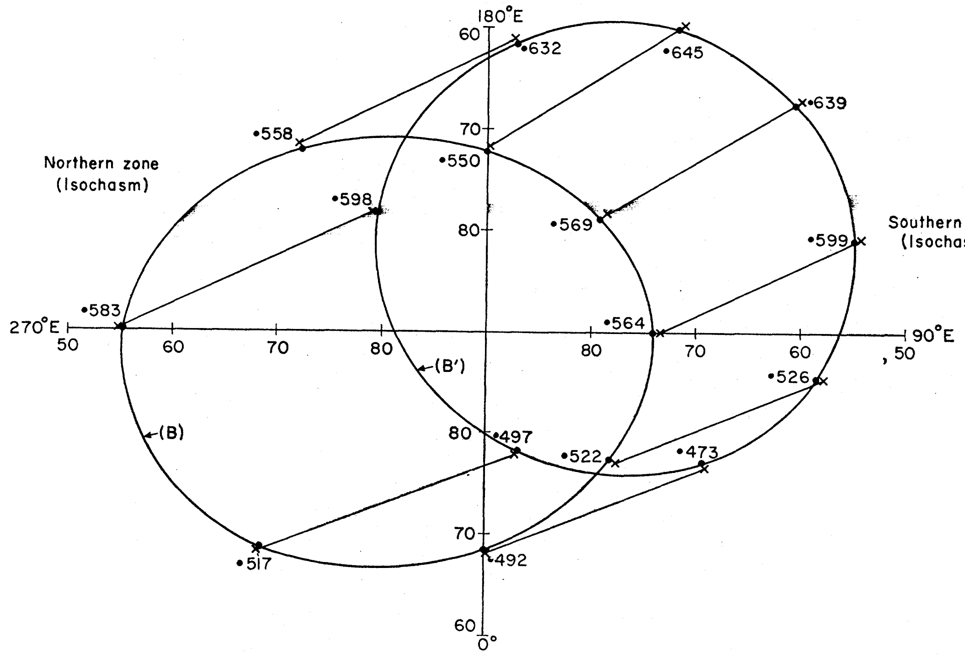

FIG. 6. Field values in cgs along (B) and (B′) of Fig. 5, basis 48 coefficients, 1955.0.

between the stream and the distorted geomagnetic field.[22–24] According to their study this is on the afternoon side of the earth. This seems likely to lead to instability, so that particles may spiral into the geomagnetic field. Near the dawn and evening half-planes or meridians the stream lines and geomagnetic field lines should be parallel, facilitating entry by drift in the direction $F\times\mathrm{grad}F$, to form aurora and the polar electrojets. The electrojets in turn have electric fields, the more intense electrojet having an electric field directed from east to west. The latter field may tend to drive spiraling particles into low latitudes to enter a trapped condition in the Van Allen region, where those of low mirror point may be absorbed later in the atmosphere, yielding x rays and radio-wave absorption at some frequencies.

If the loading of the geomagnetic field to capacity is achieved, the supply entering and forming auroral displays may also have a tendency towards instability. Thus a first theory of auroral morphology may be available indicating that the transitions from homogeneous arcs to ray arcs to draperies to pulsating surfaces, which often appear in sequence, may arise from the natural growth of instabilities. On this basis, the homogeneous arc may endure for some time because it is anchored at the base of a magnetic field line intersecting the electrically conducting E region in the Northern and Southern Hemispheres.[16]

The geomagnetic field in space and its distortions by solar streams are now being measured by magnetometers aboard earth satellites. This work supplemented by rocket probes should clarify many phenomena related to particles and fields in space.

[22] A. J. Dessler and E. N. Parker, J. Geophys. Research **64**, 2239 (1959).
[23] J. H. Piddington, J. Geophys. Research **65**, 93 (1960).
[24] E. H. Vestine, Science **130**, 897 (1959), and references cited therein.