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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

I-2-P4. Polar Magnetic Storms, Especially in the Southern Polar Region

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Various characteristics of polar magnetic storms are derived from observed data during IGY/IGC periods. (i) The electrojet area of polar elementary storm is always associated with simultaneous auroral displays, and may be named the activated area of polar storm. The areal dimensions of the activated area of a well developed polar elementary storm are about 500 km in magnetically N-S direction and 2,000 km or more in E-W direction. (ii) If these dimensions of the activated area are taken into account, simultaneity and similarity of activation between geomagnetically conjugate areas in the North and South polar regions can be established with observed data. (iii) The average *DS*-field in the South is consequently just a mirror image of the North *DS*-field with respect to the geomagnetic equatorial plane. (iv) However, there exists a definite discrepancy between geomagnetic variation on quiet days in the sunlit cap and in the dark one. The *Sq*-field in the dark polar region is almost an extension of the well-known middle and low latitude *Sq*-field, but in the sunlit polar region, a particular field *Sq*(*SP*) as shown in Fig. 8 is added. The existence of the *Sq*(*SP*) field may indicate that the solar wind is coming in always to the sunlit polar cap area. (v) Theoretical analyses of geomagnetic, auroral and ionospheric data observed simultaneously in the auroral zone show that the activated area of polar storms in the auroral zone can only be caused by an electron beam of 10 kev in average energy, having an areal cross section of the activated area. It is concluded from observations that electromotive force driving the electrojet is independent of the flux density of the impinging electron stream. (vi) Protons of $10-10^2$ Mev in energy in the incoming solar wind seem to be mainly responsible for the polar cap disturbances, but it seems likely that electrons must also be considered for explaining the polar cap geomagnetic disturbances.

§ 1. Constitution of Polar Storms

As already been confirmed on basis of the Second Polar Year data[1], individual polar magnetic storms are generally constituted of one or several polar elementary storms, which are now named "polar sub-storms" by Chapman[2]. This fact is re-confirmed in some more details in cases of north and south polar storms during the IGY/IGC period. Fig. 1 illustrates an examples of polar elementary storm in the northern hemisphere. The upper diagram shows the distribution of overhead equivalent currents in the northern hemisphere, while the lower one shows an enlarged illustration of the part of polar electrojet, together with distribution of simultaneous auroral luminosity, which is obtained from all-sky camera data by means of an ASCA-photoelectric analyzer[3]. As shown in this example, the active area of a polar electrojet is in approximate agreement with the active area of simultaneous auroral displays. Fig. 2 illustrates an example of distribution of electrojet and simultaneous aurora at initial stage of a polar elementary storm, where the width of auroral active area is very narrow and, at the same time, the corresponding electrojet is also thin. If we look at the magnetically N-S cross section of the electrojet and auroral distribution, as shown, for example, in Fig. 3, we may find that the location and width of electrojet is almost the same as those of the simultaneous auroral active zone. As illustrated in Fig. 4 further, when an electrojet moves northwards the simultaneous active zone of aurora moves together with the electrojet. We may therefore conclude that the active area of the polar

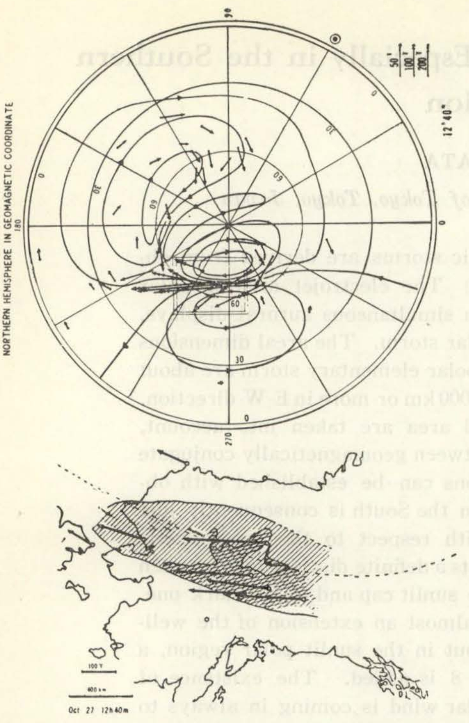


Fig. 1. An example of polar elementary magnetic storm. The lower diagram shows a part of polar electrojet (a part within the square in the upper diagram), together with distribution of auroral luminosity (shadowed area).

Fig. 2. An example of distribution of geomagnetic disturbance and auroral luminosity at initial stage of polar elementary storm.

electrojet is always accompanied by auroral displays. This active area of aurora as well as electrojet may be called here temporarily an activated area of polar storm.

According to the results of analyzing IGY/IGC data, dimensions of the activated area for a well developed polar elementary storm are about 500 km in magnetically N-S direction, and about 2,000 km or more in magnetically E-W direction.

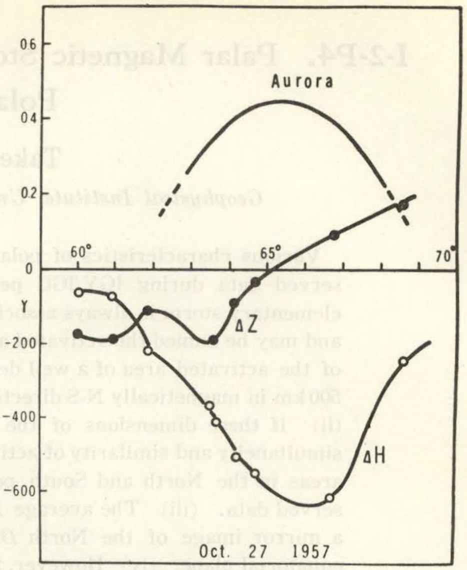


Fig. 3. Example of magnetic N-S distribution of polar magnetic disturbance and aurora.

§ 2. Connection between North and South Polar Storms

It seems therefore that, in case of a well developed polar elementary strom, a beam of charged particles having the cross section of the activated area is flowing into the auroral zone upper atmosphere from the outer space along geomagnetic lines of force, though the activated area is further composed of a number of thinner activated belts which can vary in position as well as in form. Presumably, the beam may flow in simultaneously to both geomagnetically conjugate areas, one being in the North while another in the South.

For example[4], correlation coefficient between horizontal disturbance forces in case of polar elementary storm at Baker Lake (BL) in Canada, and at Little America (LA) in Antarctica amounts to 85%. BL and LA are almost exactly conjugate to each other for magnetic latitude, but they are apart by about 600 km for magnetic longitude. If we take Churchill (Ch) in Canada instead of LA in Antarctica, the correlation coefficient between geomagnetic disturbances at BL and Ch is only about 50%. BL and Ch are situated nearly along the same geomagnetic meridian, but they are apart by about 500 km in magnetically N-S direction. If we take into consideration the average dimensions of the activated area of polar elementary storm,

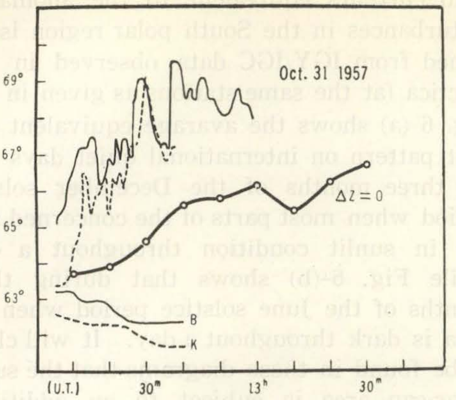


Fig. 4. Example of simultaneous movement of auroral zone electrojet (represented by $\Delta Z=0$ line) and auroral luminous zone, represented by north boundary (upper curves) and south boundary (lower curves). Full and broken curves for auroral boundary lines are due to two independent estimations from two different stations.

the above-mentioned result can satisfactorily be explained.

More general studies on this problem, based on Q-indices, carried out by Fukushima and Kokubun[5], have been led to a similar conclusion. We may therefore conclude that, in case of a polar elementary storm, a corpuscular beam is coming simultaneously to both geomagnetically conjugate areas.

However, there is still a question about definition of geomagnetic conjugation; namely, there would be

(a) static conjugate pair, and
(b) dynamic conjugate pair.

The static conjugate pair may be defined as being simply conjugate with respect to the static geomagnetic field, while the dynamic conjugate points as conjugate mirror points of moving charged particles trapped by the geomagnetic field[6),7)].

Owing to a limit of the resolving power caused by the fairly large dimensions of the activated area, and also owing to insufficiency of existing networks of observatories, the problem of "which conjugate points should be adopted" has not yet been solved from observational standpoint.

Another remark on the present problem will be the fact that the correlation between geomagnetic disturbances at nearly conjugate points becomes definitely poorer in daytime than in night time. This may partly be due to the fact that daytime polar storms are much smaller than night-time storms. But, in addition to that, it has been found that the polar region in daytime is covered by particular upper atmospheric disturbances, which take place only when the polar region is in sunlit condition. This problem will be discussed in § 4.

§ 3. The South *DS*-field and Antarctic *K*-Indices

Fig. 5 illustrates the average *DS*-field in the South polar region. This average *DS*-field pattern is constructed based on IGY/IGC data obtained at Scott Base, Wilkes, Little America, Syowa Base, Halley Bay and Macquarie Island in Antarctic region. The *DS*-field in the South is also constituted of a number of polar elementary storms. The characteristic of South-*DS* field is therefore quite the same in its constitution as the North-*DS* field. The South-*DS* field pattern is just a mirror image of the North-*DS* field with respect to the geomagnetic equator. This result may be absolutely consistent with the fact that there is a good correlation between individual polar storm disturbances at a point in the North and its magnetically conjugate point in the South.

On the other hand, general magnetic activities in the South polar region may be represented by average K-indices in this area. The Antarctic K-indices are defined in this

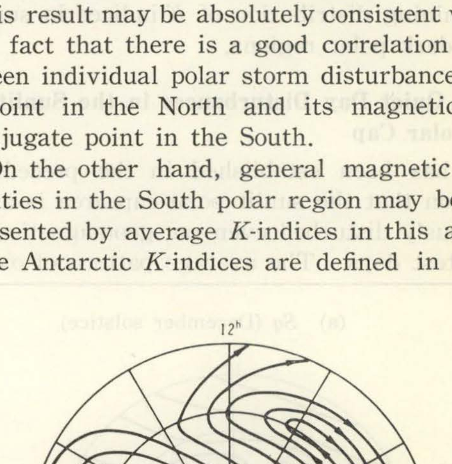


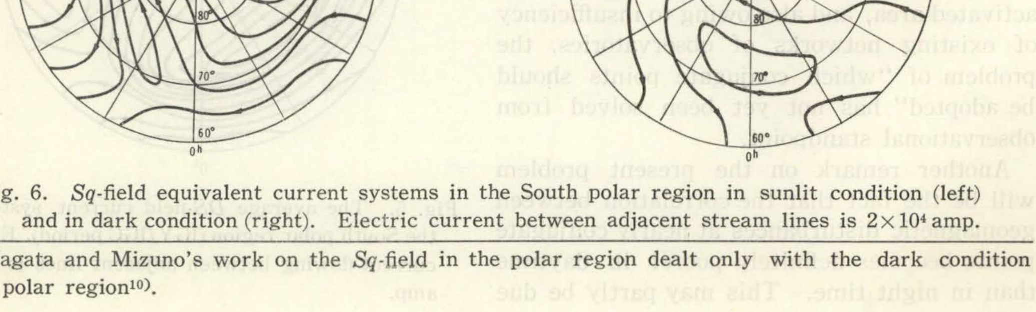
Fig. 5. The average *DS*-field current system in the South polar region (IGY/IGC period). Electric current flowing between adjacent lines is 5×10^4 amp.

report as the average values of K-indices at 8 Antarctic stations. (Hallett, Macquarie Is., Mawson, Mirny, Scott, Syowa, Wilkes, and Vostok). A whole year series of the Antarctic K-indices thus defined is in good agreement with that of K_p-indices, the correlation coefficient between them throughout a year of 1959, for example, amounting to 81%[8]. However, if we look at the month-to-month variation of the correlation between the Antarctic-K and K_p (which is essentially composed of northern high latitude K-values), we can find a definite seasonal variation such as follows: namely, the geomagnetic field in the sunlit area in the polar region, especially in the polar cap, is appreciably disturbed, even when the geomagnetic activity as a whole is extremely quiet, and consequently the geomagnetic field in the dark side polar area is very quiet. In other words, the geomagnetic field in the sunlit polar area alone is disturbed even when the other parts of the earth are geomagnetically quiet. The same conclusion has been obtained by Fukushima[9] by examining distribution of K-indices in sunlit and dark polar regions.

§ 4. Quiet Day Disturbances in the Sunlit Polar Cap

It has been established in the preceding section that the sunlit polar-cap area is anomalously disturbed even on geomagnetically quietest days. The average pattern of overhead currents equivalent to the anomalous disturbances in the South polar region is obtained from IGY/IGC data observed in Antarctica (at the same stations as given in § 3). Fig. 6-(a) shows the avarage equivalent current pattern on international quiet days during three months of the December solstice period when most parts of the concerned area are in sunlit condition throughout a day, while Fig. 6-(b) shows that during three months of the June solstice period when the area is dark throughout a day. It will clearly be found in these diagrams that the sunlit polar-cap area is subject to an additional geomagnetic daily variation of a particular type superimposed on an extension of the well-known Sq-field in middle and low latitudes on the quiet days, while the geomagnetic variation in the dark polar cap on the quiet days is almost an extension of the Sq-field alone.*

Fig. 7 illustrates the current pattern of Sq (December solstice) minus Sq (June solstice) in the South polar region. It seems likely that this pattern represents the particular sunlit polar-cap variation superimposed on (the extension of the Sq-field in middle latitudes in summer solstice time) minus (that in winter solstice time). Then, Fig. 8, which is obtained by subtracting the summer-winter inequality of the extension of the middle-latitude Sq-field from Fig. 6(a), may represent the real pattern of the particular sunlit polar-



(a) Sq (December solstice)

(b) Sq (June solstice)

Fig. 6. Sq-field equivalent current systems in the South polar region in sunlit condition (left) and in dark condition (right). Electric current between adjacent stream lines is 2×10^4 amp.

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* Nagata and Mizuno's work on the Sq-field in the polar region dealt only with the dark condition of the polar region[10].

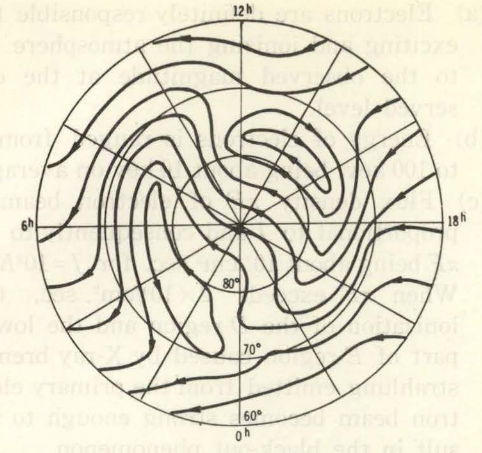

Fig. 7. *Sq* (Dec. solstice)–*Sq* (June solstice) current pattern. Electric current between adjacent stream lines is 2×10^4 amp.

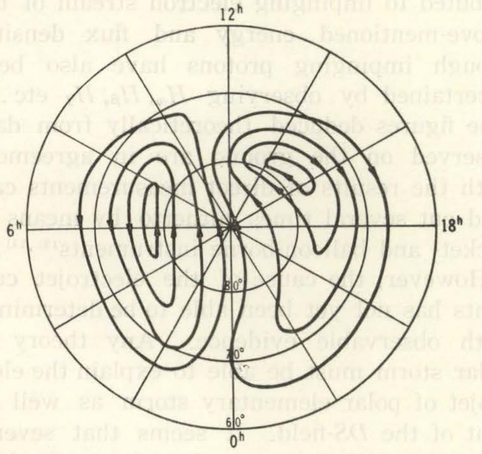

Fig. 8. The additional sunlit polar cap current pattern. *Sq*(*SP*) (Electric current between adjacent lines is 2×10^4 amp.).

cap geomagnetic variation. As will be seen in this figure the equivalent current pattern of the particular quiet-day variation in the sunlit polar cap, denoted here by *Sq*(*SP*), seems to have several definitely regular characteristics. Namely, (a) the area of current flowing of *Sq*(*SP*) is limited within the polar cap; (b) the direction of currents over the central part of the polar cap is from 23^h towards 11^h in local time; (c) the current density is definitely larger in 11^h side than in 23^h side, amounting to 1 mA/cm or more in the former.

§ 5. Main Origin of Polar Elementary Storms

From a large number of data observed at Syowa Station in the South auroral zone, it can be concluded that very close inter-relationship does always exist among magnitude of geomagnetic variation, zenith auroral luminosity and electron density in the *E*-region within the activated area of polar storm[11]. Fig. 9 illustrates such an example, where variations in the geomagnetic three components, zenithal luminosity of auroral green line (λ 5577), average brightness of aurorae over all sky and the top frequency of *Es* are shown from the top to the bottom.

Within the activated area of well developed polar storms, magnitude of geomagnetic horizontal disturbance vector (ΔH) is very closely connected with the absolute luminosity of simultaneous auroral green line (J), as shown in Fig. 10. This relationship can be ex-

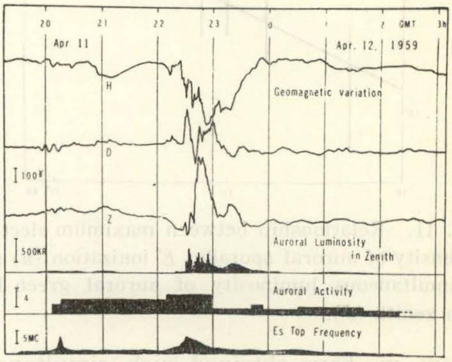

Fig. 9. Example of simultaneous observations of geomagnetic variation in the three components, zenithal luminosity of auroral green line, average brightness of all sky aurora and top frequency of auroral sporadic *E* ionization.

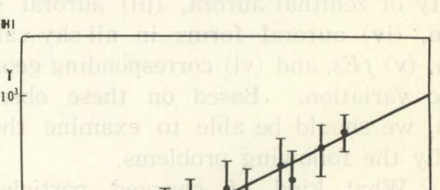

Fig. 10. Relationship between magnitude of horizontal disturbance vector of polar magnetic storm (ΔH) and simultaneous luminosity of auroral green line in zenith (J).

pressed as

$$J = 3\times10^{-3}(\Delta H)^2 \quad KR/\gamma^2 .$$

On the other hand, maximum electron density n of simultaneous auroral sporadic E ionization is also connected with J in such a way as shown in Fig. 11, and can be expressed as

$$J = 5\times10^{-10}n^2 \quad KR/(\text{electron/cc})^2 ,$$

provided that J does not exceed 2×10^3 KR in its absolute intensity. In case of severe polar storm having J greater than 2×10^3 KR, the ionogram usually shows the auroral zone blackout.

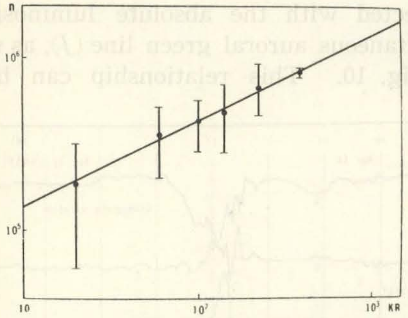

Fig. 11. Relationship between maximum electron density of auroral sporadic E ionization (n) and simultaneous luminosity of auroral green line in zenith (J).

Now, we have obtained such simultaneous data of the activated area of polar elementary storms (at least at Syowa Station) as follows: (i) altitudes of the lower boundary of aurora and the sporadic E layer, (ii) absolute luminosity of zenithal aurora, (iii) auroral spectrum, (iv) auroral forms in all-sky camera data, (v) fEs, and (vi) corresponding geomagnetic variation. Based on these observed data, we should be able to examine theoretically the following problems.

(a) What kind of charged particles is mainly responsible for energizing the activated area? Namely, electron or proton?

(b) How much is the energy of energizing particles?

(c) How much is the flux density of a beam of energizing particles?

Results of theoretical examination of these problems[12], using the standard model atmosphere, have given answers to the above-mentioned questions. The answers are

(a) Electrons are definitely responsible for exciting and ionizing the atmosphere up to the observed magnitude at the observed level.

(b) Energy of electrons is ranged from 3 to 100 kev, being about 10 kev on average.

(c) Flux density πF of electron beam is proportional to J and consequently to n^2, πF being about $10^8/\text{cm}^2$ sec, for $J=10^2KR$. When πF exceeds $2\times10^9/\text{cm}^2$. sec, the ionization of the D-region and the lower part of E-region caused by X-ray bremsstrahlung emitted from the primary electron beam becomes strong enough to result in the black-out phenomenon.

It may thus be concluded that typical main events of polar elementary storm within the activated area in the auroral zone can be attributed to impinging electron stream of the above-mentioned energy and flux density, though impinging protons have also been ascertained by observing H_α, H_β, H_γ etc... The figures deduced theoretically from data observed on the ground are in agreement with the results of direct measurements carried out several times hitherto by means of rocket- and balloon-borne instruments[13),14)].

However, the cause of the electrojet currents has not yet been able to be determined with observable evidence. Any theory of polar storm must be able to explain the electrojet of polar elementary storm as well as that of the DS-field. It seems that several theories[1),15),16),17)] proposed so far can satisfy qualitatively the above-mentioned request. In the result of the present report, however, an important additional characteristic of the elementary electrojet may be derived. It is as follows.

Increase in n in the E-region is evidently proportional to increase in electric conductivity σ in this region, while ΔH is proportional to additional overhead currents ΔI, as proved definitely by Oguti[18)]. Since $J\propto n^2$, $J\propto(\Delta H)^2$ and therefore $n\propto\Delta H$, it will be deduced that $\Delta I\propto\Delta\sigma$. This would mean that electromotive force E driving the electrojet must be invariant, being independent of ionization which is parabolically connected with the flux density of impinging electrons. From this view point, either theory[19)] of transference of electric field in the outer space, (practically in the current ring), to the earth's auroral zone atmosphere or the dynamo-theory[1),17)] may be able to survive for explaining the origin of the electrojet.

§ 6. Main Origin of Polar-Cap Disturbance

As for the agency of activating the polar-cap disturbances, it has been agreed among most scientists that protons having $10\sim10^2$ Mev in energy are mainly responsible for the polar-cap black-out[20)]. In the present report, *Sq(SP)* in the sunlit polar-cap area is newly discovered. This fact may indicate that the solar wind is coming in to the sunlit polar-cap area even on magnetically quiet period, as suggested theoretically by Dungey[21)].

An interesting feature roughly common in all kinds of polar-cap geomagnetic disturbances will be the fact that the equivalent currents in the central part of the polar cap direct either towards about 10^h in local time or just opposite, namely, towards about 10^h for *DS*, *SSC*, and *Sq(SP)*, while towards about 22^h in case of *SSC**.

Either the dynamo-theory (Obayashi[22)]) or a theory of impression of positive and negative charges separately to the polar-cap ionosphere from outside, resulting in two electric current vortices as the Hall currents, may be considerable for explaining these phenomena. In the former theory, a reversal of ionospheric wind direction, which might be attributable to reversal of wind direction at different levels, must be assumed in case of *SSC*. In the latter theory, not only proton beam but electron beam also must be taken into account always simultaneously, and further reversal of horizontal polarization of impinging beam must be assumed in case of *SSC**. Generally speaking, however, it would be preferable to presume that the *Sq (SP)* and the polar part of *DS* are due to the Hall currents (of electrons) caused by twistings magnetic lines of force frozen in the solar wind plasma coming to the polar cap *E*-region from the boundary of the earth's cavity where the twistings are produced by the general flow of the solar wind (similar idea to Dungey's I-1A-P2, and Hines' I-3-4). In addition to this phenomenon, the activated area of high electric conductivity in the auroral zone caused by impinging electron beams may cause a modification of the *DS*-field and the auroral zone electrojet.

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Discussion

Dungey, J. W.: Your quiet day result is very interesting. Do you think that on exceptionally quiet days the auroral zone is at higher latitude than normal?

Nagata, T.: I have not yet examined your point in detail. But, I feel that the auroral zone has no particular sunlit enhancement.

Martyn, D. F.: The interesting "*Sq*" polar current pattern may be excited both in the dark and sunlit polar caps; it would only show up however when the conductivity of the ionosphere was high enough—i.e. in the sunlit cap. It should also be possible to use this polar current pattern to deduce the drift *F2* ionisation in the dark polar cap—a subject which awaits adequate explanation.