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# A MODEL FOR THE PROPAGATION OF THE WESTWARD TRAVELING SURGE

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## Abstract

A unified model is developed for the propagation of the Westward Traveling Surge (WTS) which can explain the diversity in the observed surge characteristics. We start with the Inhester-Baumjohann model for the surge region which implicitly includes both the Hall and Pedersen currents. It is found that precipitating electrons at the conductivity gradient modify the gradient, causing it to propagate as a wave front. The velocity of propagation is directly dependent on the ionization efficiency of the precipitating electrons and, therefore, increases dramatically when they become more energetic during substorm onsets. For example, we predict that when the incident electron energy changes from 1 keV to 10 keV the surge velocity should increase from 2 km/s to 34 km/s. The direction of the surge motion depends on the presence of polarization charges on the poleward surge boundary. This is related to the efficiency with which the poleward ionospheric currents are closed off into the magnetosphere by the field-aligned currents. Inclusion of the electron-ion recombination rate modifies the surge propagation velocity and leads to explicit expressions for the conductivity profile. Sufficient precipitation current is required to overcome electron-ion recombination in order for the surge to expand. When the precipitating current is less than this threshold the WTS retreats. Therefore, the model describes the ionospheric response to both the expansion and recovery phases of the

magnetic substorm.

## 1. Introduction

The Westward Traveling Surge (WTS) is a primary signature of substorm onsets (Rostoker et al., 1980). In simplest terms the WTS represents the westward electrojet as it expands westward starting near local midnight during the substorm expansion phase (Tighe and Rostoker, 1981). Figure 1 shows a typical WTS profile as measured by the DMSP satellite F-6. In this example we see evidence for multiple surge structure as described by Rostoker et al. (1980). Note that the shape of the WTS is similar to that of ocean waves where the wave crest corresponds to a surge head. A more detailed examination of the surge reveals several characteristic features of the phenomena. These are 1) the surge moves in discrete jumps or steps (Wien and Rostoker, 1975; Pytte et al., 1976). 2) Instantaneous velocities of up to 30 km/s have been observed in the leading branch of the westward electrojet (Opgenoorth et al., 1983; Yahnin et al., 1983; G. Rostoker, private communication). However, a typical surge velocity is on the order of 1.0-2.0 km/s (Pytte et al., 1976). 3) The energy of the precipitating electron flux associated with the surge region is usually in the keV range (Meng et al., 1978). 4) At the head of the surge there exists an intense upward field-aligned current carried by energetic precipitating electrons. This current is concentrated within an area of at least 100 km x 100 km($1^o$ x $1^o$) with an average intensity of 1-10 $\mu A/m^2$ and can be modelled as a line current carrying $\cong 10^5$ A (Inhester et al., 1981). The slab model developed in section 2 can be applied to both the surge head and to the western precursor region.

Steady-state models of the WTS have been developed by Hughes and Rostoker, 1979; Rostoker and Hughes, 1979; and Tighe and Rostoker, 1981 using primarily ground based observations. By incorporating STARE data Inhester et al., 1981 have developed a comprehensive static model of the electrodynamic structure within the surge. Kan et al. (1984) have pointed out the importance of ionospheric current closure on the poleward surge boundary. Using static conductivity models they show that closure is responsible for the westward intrusion of highly conductive regions. In the present dynamical model we explicitly show how closure determines the surge direction and, in contrast to their conclusions, find that the surge speed does not necessarily depend on the time rate of change of closure.

In this paper we develop a dynamic model for the propagation of the WTS. As shown in the next section we explicitly utilize the closure concept and incorporate it with elements of the Inhester-Baumjohann model (Baumjohann, 1983). The motion of the WTS in the midnight sector is considered to be controlled by three mechanisms. These are: a) the energy and intensity of the precipitating electrons, b) the electron-ion recombination rate, and c) the degree of current closure on the poleward boundary of the surge. Closure is governed by the parameter $\alpha$ which is a measure of the degree to which the ionospheric Hall current is continued into the magnetosphere at the poleward boundary. (See discussion near equation (2) for more details.) In our context strong current closure ($\alpha = 1$) implies full continuation of the ionospheric Hall current system into the magnetosphere via field-aligned currents. Both $\alpha$ and the precipitation energy represent the magnetospheric input to the surge dynamics. The mechanisms describing these parameters are outside the scope of the present paper.

Upward field-aligned currents in the WTS are most intense where the conductivity gradient is largest. These currents are carried by precipitating electrons which modify the conductivity gradient through enhanced ionization. A wave equation is derived for the propagation of the conductivity gradient. The phase velocity is proportional to $V_{dt}QH$ where $V_{dt}$ is the magnitude of the total E x B drift velocity and QH is the height-integrated ionization efficiency for precipitating electrons at the conductivity gradient. This velocity is greatly enhanced when the average electron energy increases from 1 keV to 10 keV. For example, a 10 mV/m electric field implies a surge velocity of approximately 3.7 km/s for 1 keV incident electrons whereas 10 keV incident electrons will drive the surge at approximately 34 km/sec. (See Table I for details.) We see no direct connection between this propagation mechanism and that based upon an ion-acoustic wave as proposed by Kan et al. (1984).

The effect is to produce jumps in the surge velocity whenever the precipitating energy spectrum near the surge head is sufficiently hard. As shown below, it is even possible to have abrupt northeastward surge motion if there is overclosure at the poleward boundary (i.e. $\alpha > 1$). Thus, even this simplified model provides coherence to the diversity of observed surge propagation characteristics.

In section 2 the simplified model is developed for the WTS where electron-ion recombination effects are ignored. The magnitude of the surge velocity and its direction are derived. In section 3 we investigate the role of electron-ion recombination effects. We find that the recombination rate modifies the surge velocity, determines the conductivity profile at the boundary and is responsible for the retreat of the enhanced conductivity region and the associated electrojet during the recovery phase.

## 2. A model for the westward traveling surge

We start with the slab model for the WTS near local midnight as given by Baumjohann (1983) and as shown in Figure 2. In this section we only consider the motion of this slab. The results will be applied to the WTS in the discussion section. For clarity the stated propagation directions are defined for the WTS occurring in the northern hemisphere. An effective westward electric field, $E_o$, in the surge region drives a northward Hall current. This electric field is composed of the large scale convection field and that produced by negative charge buildup at the surge head. The northward current is closed into the magnetosphere by the precipitating electrons at the conductivity gradient on the northern boundary. The

Hall current is

$$J_H = \Sigma_H E_o \tag{1}$$

However, the net ionospheric current reaching the northern boundary may be unequal to $J_H$ depending on the presence of boundary polarization charges as indicated in Figure 2. This boundary polarization charge produces a southward polarization electric field, $E_p$, as shown in the figure. This electric field gives rise to an associated Pedersen current, $J_p = \Sigma_p E_p$. Thus, the net current reaching the northern boundary is $J_n = J_H - J_p = \Sigma_H E_o - \Sigma_p E_p = \alpha J_H$, where the parameter $\alpha$ is a measure of the degree of continuity (closure) of the Hall current on the northern boundary via the Birkeland currents, assuming no closure currents in the ionosphere outside the slab. It is an undetermined parameter in our theory that reflects the ionosphere-magnetosphere coupling. The value $\alpha = 0$ denotes no closure, the value $\alpha = 1$ full closure and $\alpha > 1$ overclosure (i.e. a negative polarization charge on the northern boundary produced by excess Birkeland currents).

We define a coordinate system as shown in Figure 2 such that the z-axis points perpendicular to both the current channel and the earth's magnetic field. The x-axis points parallel to the current channel. When applied to the westward electrojet the x-coordinate is approximately west and the z-coordinate north. For simplicity, in the following model we define x as pointing due west and z as pointing due north.

The precipitating Birkeland current is the divergence of $J_n$ as given by

$$j_{\parallel} = -\partial (E_o \alpha \Sigma_H)/\partial z$$

$$= -E_o \alpha \partial \Sigma_H/\partial z \tag{2a}$$

where $\alpha$ is the coupling parameter defined above. A meaningful

$\alpha$ can only be defined where there is a conductivity gradient. To be more precise consider current conservation across the boundary.

$$\int_{z_1}^{z_2} j_{\parallel}\, dz = \int_{z_1}^{z_2} -E_o\, \partial\, (\alpha(z)\ \Sigma_H(z))dz \qquad (2b)$$

If $\alpha$ = const. within the boundary region ($z_1 < z < z_2$) then

$$\int_{z_1}^{z_2} j_{\parallel}\, dz = \alpha\, J_H(z_1) \qquad (2c)$$

This is another way of expressing the overall current continuity at the northern boundary. An $\alpha < 1$ implies the presence of positive polarization charge. We associate $j_{\parallel}$ with the flux of precipitating electrons through the relation $j_{\parallel}/e$. This assumes that the precipitating protons are not important in the surge region (Akasofu et al., 1969) and that the dominant current carriers are energetic (keV) electrons (Meng et al., 1978; Inhester et al., 1981). This is consistent with the enhancement of keV electrons obseerved during the passage of the WTS (Opgenoorth et al., 1983). For simplicity we shall ignore possible spatial variations in both $\alpha$ and $E_o$. The ratio of the Hall to Pedersen conductivity (R) is considered to be a function of z only.

In the following derivation we recognize that precipitating electrons through ionization modify the conductivity. The local time rate of change of the Hall conductivity is

$$\partial \Sigma_H / \partial t \simeq (eH/B)\, \partial n / \partial t \qquad (3)$$

where n is the ion density which is related to the precipitating electrons through the ionization efficiency, Q (Rees, 1963; Jasperse and Basu, 1982). Thus,

$$\partial n/\partial t = Q\ j_{\parallel}/e - \sigma_r n^2 \tag{4}$$

where here Q is the average number of ions produced per incident electron-m and H is the appropriate height interval for Q and $_r$ is the electron-ion recombination coefficient in the ionosphere. (The unit ions/electron-m when multiplied by the unit for flux (electron/m$^2$ -s) becomes ions/m$^3$ -s, the ion production rate per unit volume). Equation (4) is general in that an average Q can be defined for any incident spectrum. The ionization rate is then this average Q times the total incident electron current providing the net backscattered current is small. For example, the presence of a parallel electric field will effectively eliminate any upward electron current contribution (Evans, 1974). If we assume that only the energetic component (keV electrons) carry the parallel current then the Q in equation (4) is identical to the Q/F defined by Rees (1963).

We initially treat the limiting case where $-j_{\parallel}Q/e >> \sigma_r n^2$ in order to illustrate the physical principles involved. The full equation is solved below in section 3. There we show that the simple approximation is valid if $j_{\parallel} >> 3$ A/m$^2$ when $E_{incid} > 1$ keV. The sign in front of $j_{\parallel}$ in equation (4) indicates that positive current is flowing away from the earth. Combining eqs. 2-4 we obtain

$$\partial \Sigma_H/\partial t = -(Q\ H\ E_o\ \alpha)/B\ \partial \Sigma_H/\partial z \tag{5}$$

which is a wave equation with a phase velocity given by

$$V_n = Q\ H\ \alpha\ V_d \tag{6}$$

where $V_d = E_o/B$. This is easily found by making a Galilean transformation $\Sigma_H = \Sigma_H(z')$, where $z' = z - V_n t$.

Figure 3 shows the estimated variation of QH with incident electron energy as taken from Figure 2 of Rees, 1963. From this figure it is seen that a 1 keV monoenergetic precipitating flux imples QH $\simeq$ 10 and for a 10 keV flux QH $\simeq$ 90. Thus, when the energy spectrum of the precipitating electrons hardens the boundary velocity can increase by factors of ten. Meng et al. (1978) have measured a very hard precipitating energy spectrum in the surge region. We argue that the surge velocity is related to the production of energetic electrons connected with substorm onsets. According to this mechanism the surge velocity should increase dramatically during substorm onsets as has been observed by Samson and Rostoker (1983).

We now consider the western boundary (i.e. the surge head). The dynamics of this boundary is connetcted to the propagation of the poleward boundary through closure. That is, a small $\alpha$ imples a large $E_p$ which drives a westward Hall current that adds to the Pedersen current driven by $E_o$. The total westward current is given by

$$J_w = \Sigma_p E_o + \Sigma_H E_p \quad (7)$$

From the above definition of $J_n$ we have

$$J_p = (1 - \alpha)\ J_H$$

$$\Sigma_p E_p = (1 - \alpha)\ \Sigma_H E_o \quad (8)$$

Substituting this expression for $E_p$ into equation (7) leads to an $\alpha$-dependent Cowling current

$$J_w = \{1 + R^2 (1 - \alpha)\} E_o\ \Sigma_p \quad (9)$$

where

$$R = \Sigma_H / \Sigma_p$$

The precipitating current at the head of the surge is

$$J_{\parallel} = \{ 1 + R^2 (1 - \alpha) \} E_o \, \partial \Sigma_p / \partial x$$

$$= \left[ \{ 1 + R^2 (1 - \alpha) \} E_o / R \right] \partial \Sigma_H / \partial x \qquad (10)$$

where the x-axis is in the westward direction and R is considered independent of x. Note that at the northern boundary it was not necessary to assume R constant in deriving equation (5). Therefore, $E_p$ (equation (8)) may also be a function of z and our model implicitly allows polarization charge along the northern boundary. A wave equation is now derived for the western boundary associated with the surge head just as for the northern boundary. The resulting phase velocity is

$$V_w = Q \, H \, V_d \; \{ 1 + R^2 (1 - \alpha) \} / R \qquad (11)$$

We now assume that the surge head region will propagate in a direction determined by the vector sum of $V_n$ and $V_w$. The direction of the resultant surge velocity based on this idealized model is given by

$$\tan \gamma_s = V_n / V_w = \alpha R / \{ 1 + R^2 (1 - \alpha) \} \qquad (12)$$

where $\gamma_s = 0$ corresponds to due west motion. We see that the direction of the surge is highly dependent on the degree of closure on the northern surge boundary and the value of R on the western surge boundary. For zero closure ( $\alpha = 0$) the surge moves due west. For complete closure ($\alpha = 1$) the direction is almost due north $\left[ \tan \gamma_s = R \cong 3 \; ; \gamma_s \simeq 72^\circ \right]$.

The sensitivity of $\gamma_s$ to $\alpha$ is modulated by the magnitude of R. A detailed plot of $\gamma_s$ vs. $\alpha$ for various values of R is shown in Figure 4. Note that the surge direction can range from due west to northeast, where the latter condition will arise when there is significant overclosure ($\alpha > 1$) during periods of intense electron precipitation.

The magnitude of the total slab velocity, $V_{ts}$, is found from ${V_{ts}}^2 = {V_n}^2 + {V_w}^2$. Clearly, the resultant motion of the surge head is more complex than that indicated by the simple slab model treated here. (See discussion for more details.) Note that the slab velocity, $V_{ts}$, can be much larger than the E x B speed and is in a different direction. From this definition of $V_{ts}$ and equations (6) and (11) we find that

$$V_{ts} = \frac{V_d \ QH}{R} \left\{ \alpha^2 \ R^2 + (1 + R^2 \ (1 - \alpha))^2 \right\}^{1/2} \qquad (13)$$

Using the identity $\alpha^2 = (1 - \alpha)^2 - 1 + 2\alpha$ in $V_{ts}$ one finds (see Appendix) that the total slab velocity can be expressed simply as

$$V_{ts} = V_{dt} \ QH \{ 1 + 1/R^2 \}^{1/2} \qquad (14)$$

which is independent of $\alpha$ and where $V_{dt}$ is the total E x B speed as given by

$$V_{dt} = V_d \ \{ {E_o}^2 + {E_p}^2 \}^{1/2} / E_o \qquad (15)$$

Using equation (8) we have

$$V_{dt} = V_d \ \{ 1 + R^2 \ (1 - \alpha)^2 \}^{1/2} \qquad (16)$$

It has been noted by Opgenoorth et al. (1983) that the measured electric field within and south of the auroral forms connected with the passage of a WTS was typically below the threshold ( ≈ 15mV/m) of the STARE radar. This gives an upper limit to the drift velocity $V_{dt}$ of 0.375 km/s. For $V_{ts}$ (equation 14) to equal the measured surge velocity of 2.0 - 3.3 km/s QH must be, therefore, on the order of ten. This implies from Figure 2 that the mean electron precipitating energy was on the order of 1 keV, which is consistent with observations (Opgenoorth et al., 1983). More comprehensive auroral campaigns are needed to simultaneously define the parameters used in our model.

3. Effects of electron-ion recombination

In this section we include the effects of the electron - ion recombination rate on the WTS. One exact solution to equation (4) can be obtained by assuming an ionospheric-magnetospheric coupling such that $\alpha$ is equal to a constant. The equation for $\Sigma_H$ at the northern boundary is now

$$\partial \Sigma_H / \partial t = - V_n \, \partial \Sigma_H / \partial z - G \, \Sigma_H^2 \qquad (17)$$

where

$$G = \sigma_r B / eH \qquad (18)$$

and where $V_n$ is defined in equation (6).

We not look for a solution to equation (17) which is stationary in a coordinate system (z') moving with a velocity V relative to the earth's surface. Accordingly we make a Galilean transformation (z' = z - Vt). This allows equation (17) to be rewritten as

$$\Sigma_H' / \Sigma_H^2 = G/(V - V_n) \qquad (19)$$

where $\Sigma_H = \Sigma_H(z')$ and $\Sigma_H' = \partial\Sigma_H/\partial z'$. Note by definition that equation (19) is solely a function of z' in the moving frame of reference and, therefore, $\Sigma_H(z')$ is stationary in this frame. The solution is

$$\Sigma_H(z') = \Sigma_{Ho}\,(V - V_n)/(V - V_n - \Sigma_{Ho}\,G\,z') \tag{20}$$

where $\Sigma_{Ho} = \Sigma_H(0)$. Hence, choosing $\alpha$ = constant implies that the conductivity profile is hyperbolic in the moving frame. We choose z' = 0 to be where the boundary region joins the main surge region in the Inhester-Baumjohann model. Therefore, $\Sigma_{Ho}$ has the same value as the conductivity inside the surge head.

The assumed constant velocity V can now be expressed in terms of the conductivity gradient at z' = 0. To see this we first take the derivative of equation (20) and evaluate it at z' = 0. The resulting expression is

$$\Sigma_{Ho}' = G\,\Sigma_{Ho}^2/(V - V_n) \tag{21}$$

where $\Sigma_{Ho}'$ is the value of the conductivity gradient at z' = 0. The physical meaning of equation (21) is made clearer by using equation (2) and solving for V. We find

$$V = V_n - G\,\Sigma_{Ho}^2\,E_o\,\partial/j_{\parallel}(0) \tag{22}$$

We have previously shown that $V_n$ increases dramatically as the incident energy spectrum hardens. The recombination term is independent of Q and, therefore, V also increases in the same manner.

Evidently, the slab boundary will not move poleward unless

$$j_{\parallel}(0) > G\,\Sigma_{Ho}^2\,E_o\,\partial/V_n = \sigma_r n^2\,e/Q \tag{23}$$

Taking $\sigma_r \approx 10^{-13}$ $m^3/s$ (Walls and Dunn, 1974), $n = 3 \times 10^{11}$ ions/$m^3$, and $Q = 5 \times 10^{-4}$ (electron-m)$^{-1}$ ($E_{in}$ = 1 keV) we find a threshold current of 2.9 $\mu A/m^2$. This value is consistent with typical auroral current densities.

The precipitation current, therefore, must exceed some minimum value for the surge to propagate. Equation (22) also implies that if the current is below the threshold value the surge will propagate in a negative or equatorward direction. This, we believe, describes the ionospheric response during the recovery phase of a magnetic substorm. The diminishing precipitation current cannot sustain the high conductivity against electron-ion recombination and the surge head retreats.

Equation (17) can be solved at the western slab boundary in exactly the same way, except now $V_n$ is replaced by $V_w$ as defined in equation (11). The resulting effective velocity depends on the conductivity gradient at the western boundary. The conductivity gradients, therefore, must also influence the surge's direction of propagation as derived in section 2.

It should be emphasized that equation (17) could be solved because we assumed a specific ionospheric-magnetospheric coupling such that a stationary solution was possible in a moving frame of reference. No doubt the dynamical nature of the coupling is such that the conductivity profile is probably nonstationary in all frames of reference. However, the present theory qualitatively explains much of the surge phenomena using presently available data.

## Discussion

It has been observed that the WTS moves in a series of discrete steps or jumps (Wien and Rostoker (1975), Pytte et al. (1976)). This result led Rostoker et al. (1980) to define a magnetospheric substorm as allowing a series of multiple surges during the expansion phase. Each surge corresponds to an individual substorm onset which on a time average shifts the maximum poleward expansion northwestward. In the present model each surge corresponds to a temporal hardening of the precipitating electron flux energy spectrum. This temporal hardening is related to the substorm onset processes in the magnetotail and the generation of parallel electric fields which is outside the scope of the present work.

Samson and Rostoker (1983) noted the presence of associated Pi 2 signatures with the WTS. The surge marks the transition from equatorward to poleward type Pi 2 polarization signatures. The elliptical polarization of the Pi 2's is considered to be caused by the longitudinal expansion of field-aligned currents in the surge together with the conjugate reflection of field-aligned current pulses. We suggest that the same enhanced field-aligned current produces a jump in the surge velocity as predicted by the model presented here and as observed by Wien and Rostoker (1975) and Pytte et al. (1976).

The surge head may at times break off from the main body forming a separate surge. (See Figure 13 in the paper by Samson and Rostoker, 1983.) In terms of the present theory once a new conductivity gradient is established between the surge regions their relative velocity is determined by the energy spectra of the precipitating electrons at the westward head of the separate parts. The propagation of each part can be described by modelling them as a separate slab. Instantaneous velocities of up to 30 km/s have been observed at the leading branch of the western electrojet (Opgenoorth et al., 1983; G. Rostoker, private communication). This branch can be considered as a separate slab with its own model parameters. Westward velocities of 30 km/s will result from equation (11) if we assume $E_o = 10^{-2}$ V/m, $\alpha = 0$, $R = 3$ and the incident electron energy to be approximately 5 keV. The higher westward velocites at the same precipitation energy are due to the additional R-factor in $V_w$ which arises from the enhanced Cowling current when $\alpha = 0$. Yahnin et al. (1983) note that a harder precipitation energy exists inside the surge in comparison with outside the surge region which is consistent with this result.

Surges have also been occasionally observed moving in a northeasterly direction (Pytte et al., 1976). This can be explained in the present model by overclosure of the Hall current on the poleward surge boundary as shown in Figure 4. Intense electron precipitation ($\alpha > 1$) causes a poleward polarization electric field with an associated eastward Hall current that weakens the westward Pedersen current driven by the external electric field, $E_o$.

The direction of the surge motion is related to the direction of the resultant electric field. From Figure 4 it is noted that a northwestward direction corresponds to $\alpha \cong 0.8 - 0.9$. Using this result in equation (8) for $E_p$ implies that the resultant electric field points in the southwestern direction which is consistent with the results of Inhester et al. (1981).

Our results in section 2 (summarized in Table I for $\alpha = 1$) indicated that an unphysical surge velocity could occur if the incident energy spectrum is too hard. However, in section 3 we found that the surge velocity is decreased by the electron-ion recombination rate and that the magnitude of the precipitating current is important. Note also that the relation between $\alpha$ and the incident energy spectrum is unknown so that the excessive velocities given in Table I probably do not occur.

In summary, it is found that the present model predicts a wide range of complex surge phenomena depending on the ratio of the Hall to Pedersen conductivities, the degree of ionopsheric current closure into the magnetosphere and the energy spectra of precipitating electrons. The following summarizes our main results. 1. We find that the direction of the WTS depends strongly on the degree of current closure on the poleward boundary. The sensitivity of the surge direction to closure depends on the ratio (R) of the Hall to the Pedersen conductivities. 2. The magnitude of the surge velocity is sensitive to the energy spectrum of the precipitating electrons and weakly dependent on R. The ratio of the surge velocity to the measured drift velocity is independent of the degree of closure at both the surge head and the northern boundary. 3. The expansion phase of the substorm is explained by assuming that the initial arc brightening arises from a sudden hardening of the precipitating electron energy spectrum at its poleward boundary. 4. Inclusion of electron-ion recombination effects highlights the role of the precipitating current intensity in modulating the surge propagation and explains the equatorward retreat of the surge during the substorm recovery phase. 5. Details of the surge propagation depend on how the magnetosphere and ionosphere are coupled as reflected in the functional form of $\alpha$ and Q. Hence, the energy source is clearly located in the magnetosphere and a complete description of substorm phenomena must take this into account.


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## Appendix

Equation (14) is obtained from equation (13) by using the given identity. The intermediate results for the bracketed term in equation (13) are

$$(1-\alpha)^2 R^2 + 1 + R^2 + R^4 (1-\alpha)^2$$

$$(1-\alpha)^2 R^2 \quad 1 + R^2 \quad + 1 + R^2$$

$$(1 + R^2) \quad 1 + (1-\alpha)^2 R^2 \qquad \text{(A1)}$$

Comparison of this expression with equation (16) immediately gives equation (14).

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TABLE I

| $E_{incid}$(keV) | H(km) | Q(ions/$e^-$-cm) | QH(ions/$e^-$) | $V_{ts}$(km/s) ($\alpha$=1, R=3.0, E=15mV/m) |
|---|---|---|---|---|
| 1.0 | 20 | $5 \times 10^{-6}$ | 10 | 3.7 |
| 1.65 | 10 | $8 \times 10^{-6}$ | 8 | 3.0 |
| 5.60 | 7 | $7 \times 10^{-5}$ | 49 | 18.7 |
| 40.00 | 5 | $8 \times 10^{-4}$ | 400 | 150.0 |

The height-integrated ion production (QH) from precipitating electrons is listed as a function of incident electron energy. These values were estimated from Figure 2 in the article by Rees, 1963. The appropriate height interval, H, is estimated at the maximum value of Q. The incident electrons are considered to be isotropic, monoenergetic beams. The results are plotted in Figure 3. The parameter $\alpha$ is a measure of how efficiently the poleward Hall current closes into the magnetosphere, R is the ratio of the Hall and Pedersen conductivities, and E is the measured (see equation (15)) electric field in the surge region and $V_{ts}$ is the total surge velocity as defined in equation (14).

## Figure Captions

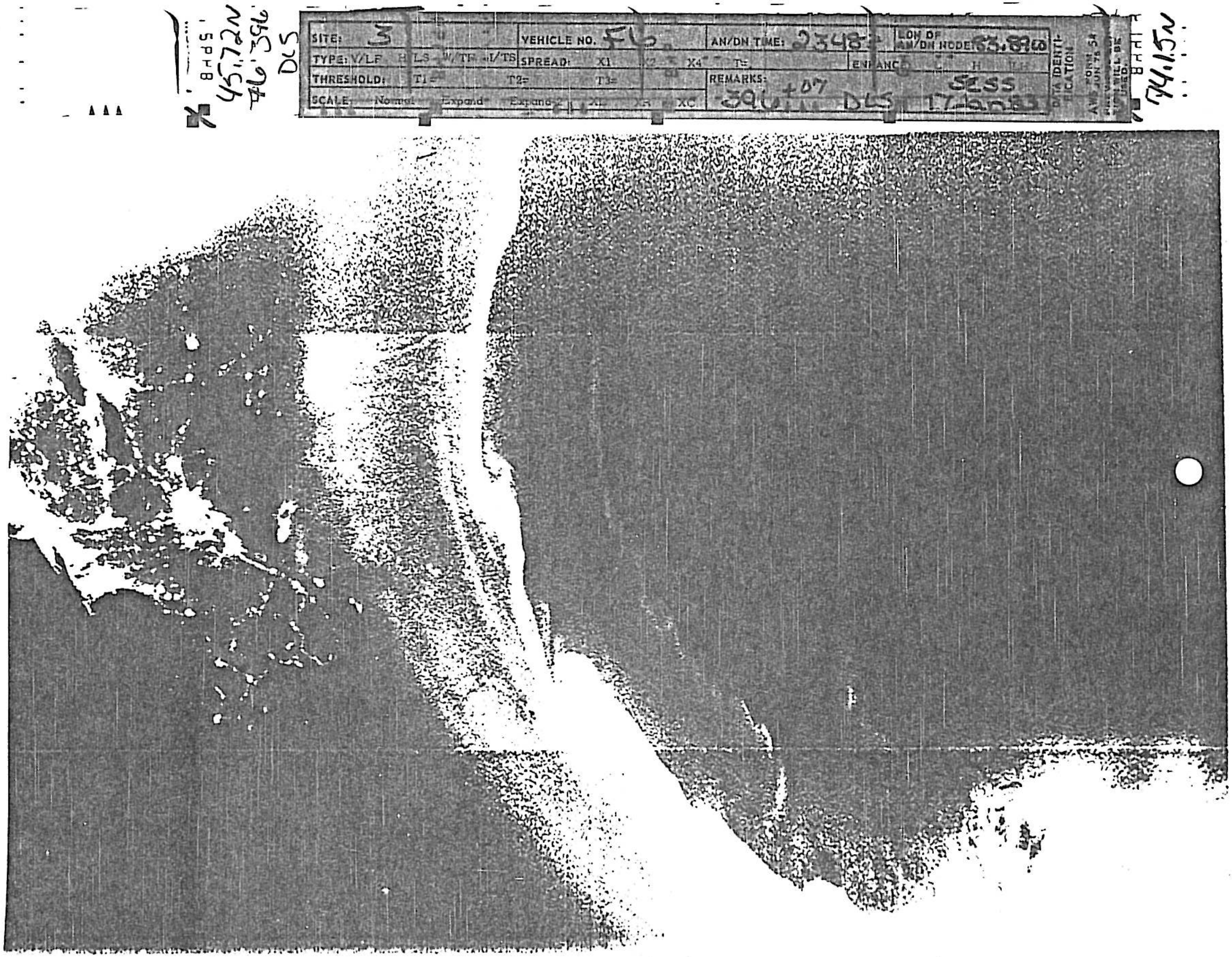
Figure 1. The aurora as photographed by the DMSP-F6 satellite on January 17, 1983. A small Westward Traveling Surge (WTS) is observed in the center of the photograph followed by a significantly larger one to the east. The overall shape of a surge is similar to that of an ocean wave where the wave crest corresponds to the surge head. In our idealized model the surge is represented as a slab as shown in Figure 2.

Figure 2. Idealized model of the WTS as proposed by Inhester et al., 1981. The total external electric field, $E_o$, drives a westward Pedersen and a northward Hall current. If the northward Hall current is not fully continued by field-aligned currents into the magnetosphere polarization charges build up on the northern surge boundary producing a southward directed electric field, $E_p$. This southward electric field produces a Hall current in the same direction as the Pedersen current from the original electric field, $E_o$. This affects the direction of the surge motion as described in the text. Negative polarization charge may also build up at the surge head due to intense electron precipitation (Inhester et al., 1981). This is treated in our idealized model by allowing a renormalization of $E_o$. In our coordinate system z points perpendicular to $E_o$ and x is parallel to $E_o$ which approximately corresponds to North and West.

Figure 3. Height-integrated ion production efficiency in the ionosphere for incident precipitating electrons. More energetic electrons produce a higher ionization density near the end-of-range. This curve is for an isotropic, monoenergetic incident beam and was taken from Figure 2 of Rees, 1963. Errors up to a factor

of two could arise from erroneous estimation of the appropriate height interval from Rees' figure 2. A reasonable fit to this curve is $QH \approx 5\ E^{1.2}$ ions/(incident electron).

Figure 4. The direction of the surge motion as a function of the closure parameter which represents the degree of Hall current closure on the northern surge boundary. The value $\alpha = 1$ implies $E_p = 0$. Also a larger value of $\alpha$ implies a more intense precipitating current with $\alpha > 1$ corresponding to a negative rather than positive charge buildup on the northern boundary. The sensitivity of the surge direction to $\alpha$ is dependent on the ratio of the Hall to Pedersen conductivities at the western surge boundary which we denote by R. Note that $\gamma_s \simeq 45^{\circ}$ corresponds to $\alpha \simeq 0.8 - 0.9$.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VEHICLE NO.
AN/DN TIME:
TYPE: V/LF
SPREAD:
THRESHOLD:
REMARKS:
SCALE:
DATA IDENTIFICATION

Fig.1

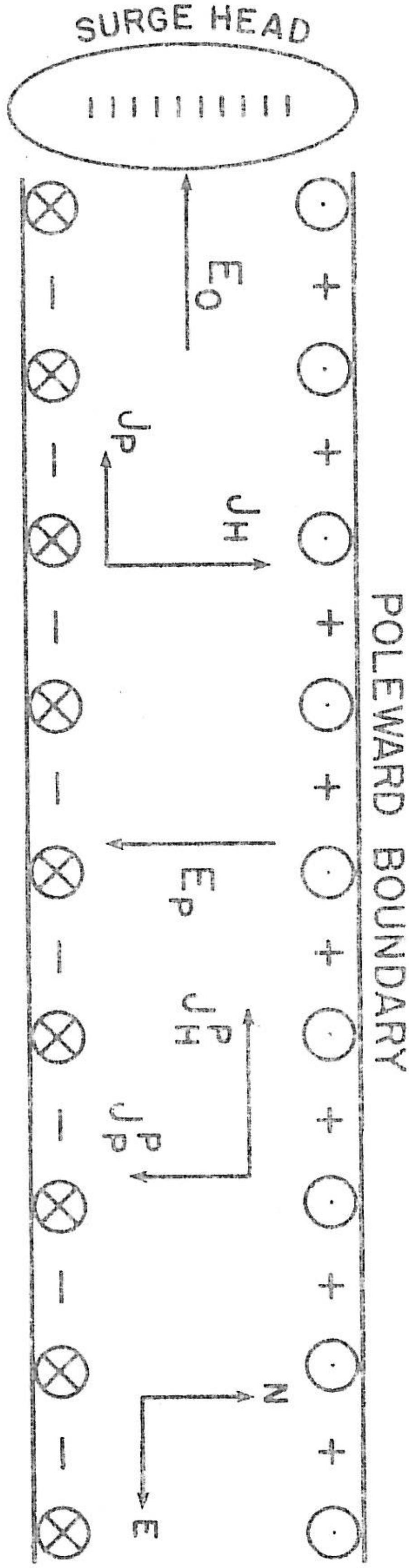


Fig.2

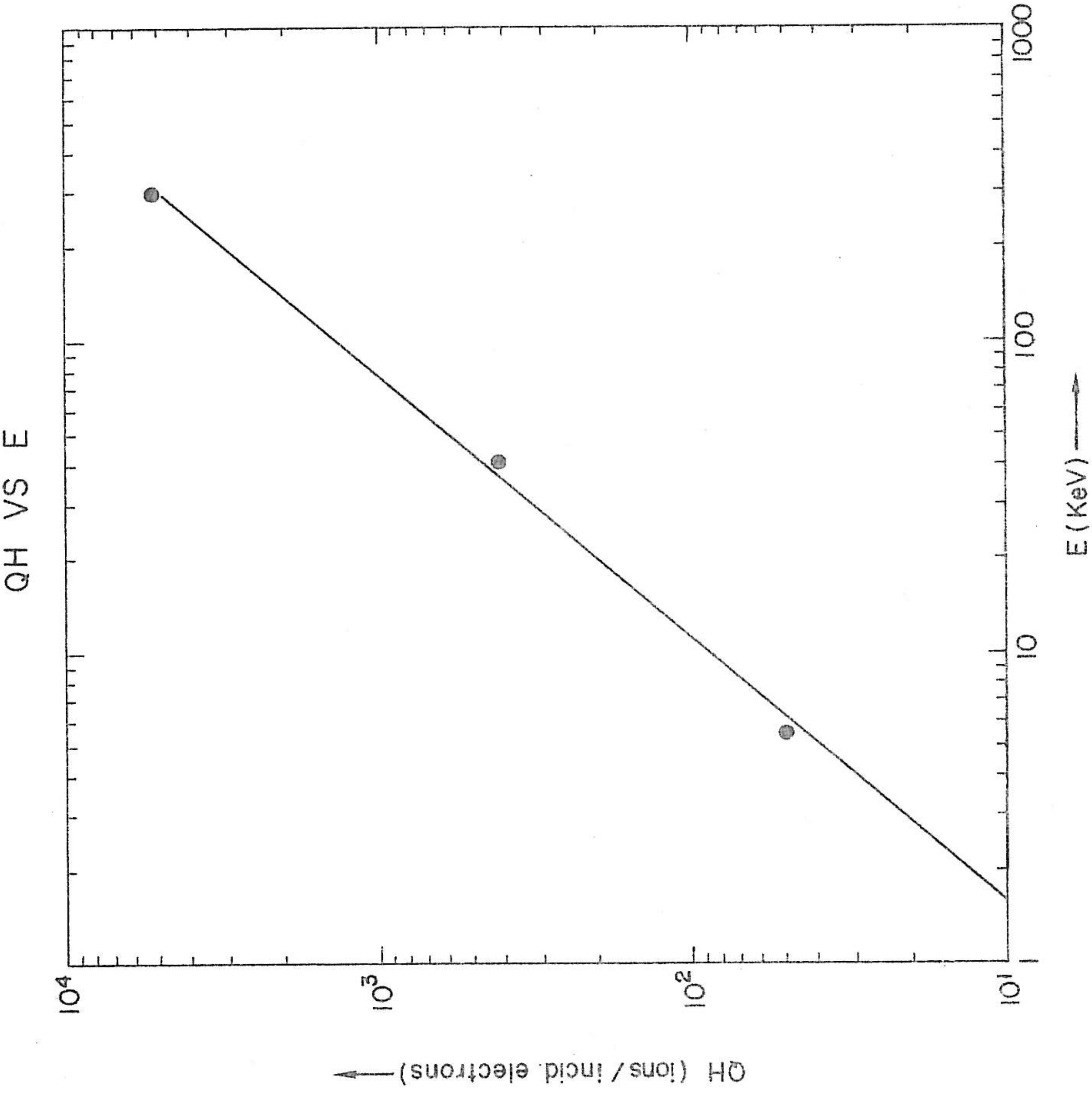
QH VS E
E (KeV)
10
100
1000
10^1
10^2
10^3
10^4
QH (ions / incid. electrons)

Fig.3

DIRECTION OF THE WESTWARD TRAVELING SURGE Vs CLOSURE ON THE NORTHERN BOUNDARY

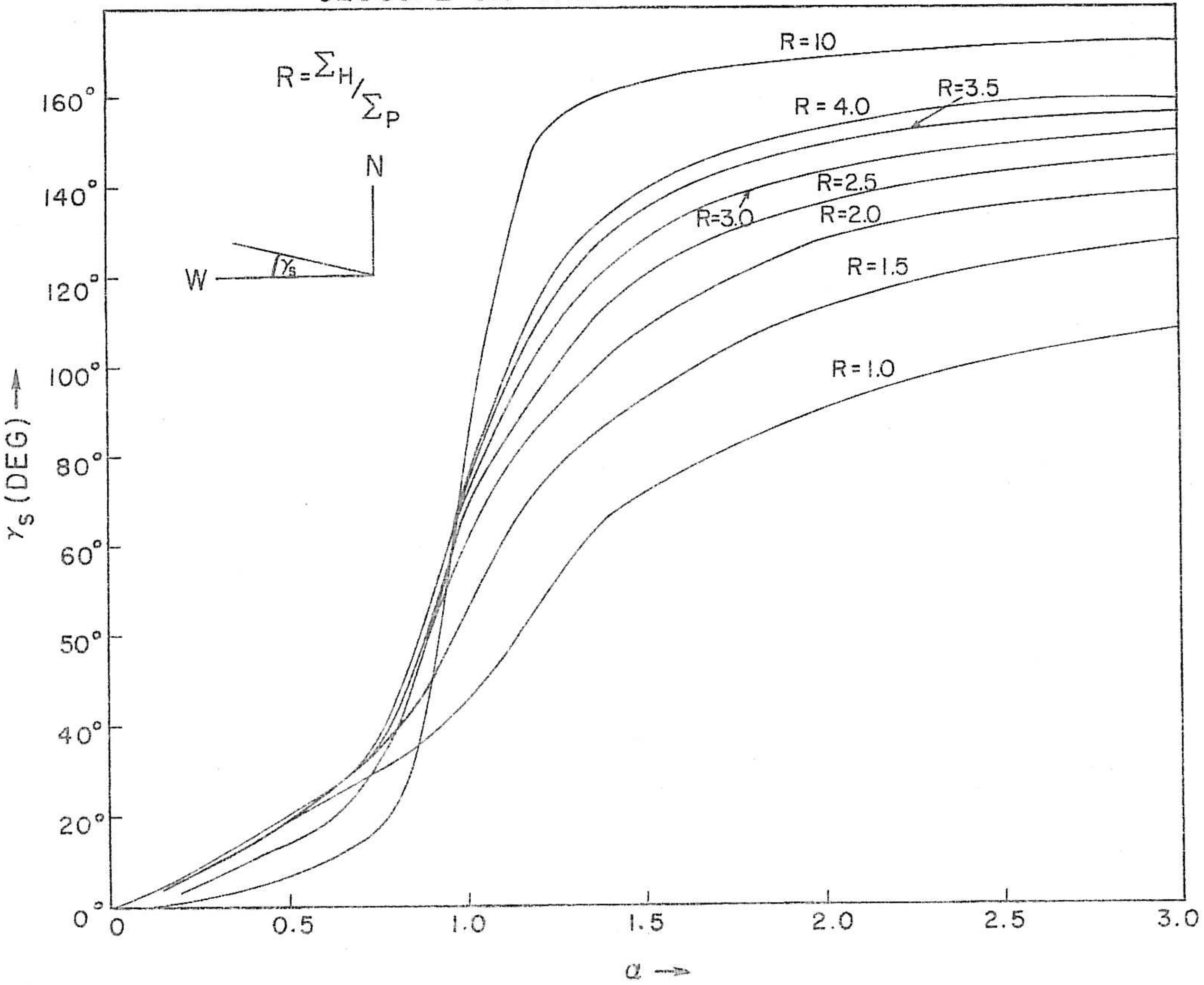


Fig. 4

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A MODEL FOR THE PROPAGATION OF THE WESTWARD TRAVELING SURGE

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A unified model is developed for the propagation of the Westward Traveling Surge (WTS) which can explain the diversity in the observed surge characteristics. We start with the Inhester-Baumjohann model for the surge region which implicitly includes both the Hall and Pedersen currents. It is found that precipitating electrons at the conductivity gradient modify the gradient, causing it to propagate as a wave front. The velocity of propagation is directly dependent on the ionization efficiency of the precipitating electrons and, therefore, increases dramatically when they become more energetic during substorm onsets. For example, we predict that when the incident electron energy changes from 1 keV to 10 keV the surge velocity should increase from 2 km/s to 34 km/s. The direction of the surge motion depends on the presence of polarization charges on the poleward surge boundary. This is related to the efficiency with which the poleward ionospheric currents are closed off into the magnetosphere by the field-aligned currents. Inclusion of the electron-ion recombination rate modifies the surge propagation velocity and leads to explicit expressions for the conductivity profile. Sufficient precipitation current is required to overcome electron-ion recombination in order for the surge to expand. When the precipitating current is less than this threshold the WTS retreats. Therefore, the model describes the ionospheric response to both the expansion and recovery phases of the magnetic substorm.

<u>Key words</u>: Aurora, Electrojet, Electron precipitation, Field-aligned current, Hall conductivity, Ionization, Pedersen conductivity, Recombination, Substorm, Westward travelling surge.