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THE EFFECTS OF GEOMAGNETIC FIELD ALIGNED POTENTIAL DIFFERENCES --ETC(U)

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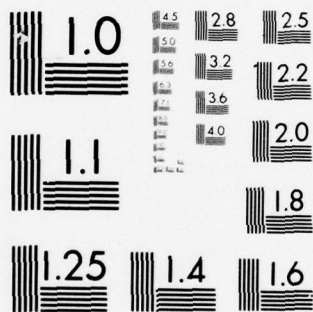
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NRL Memorandum Report 3573

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The Effects of Geomagnetic Field Aligned Potential Differences on Precipitating Magnetospheric Particles

J. H. ORENS AND J. FEDDER
Plasma Physics Division

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January 1978

This research was sponsored by the Defense Nuclear Agency under Subtask
No. SS9QAXHC066, Late Time Effects, work unit 04, Electrostatic-Ion Plume.



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3573	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) THE EFFECTS OF GEOMAGNETIC FIELD ALIGNED POTENTIAL DIFFERENCES ON PRECIPITATING MAGNETOSPHERIC PARTICLES	5. TYPE OF REPORT & PERIOD COVERED Interim Report on a continuing NRL Problem	
6. AUTHOR(s) 10 Joseph H. Owens, Joel Fedder J. H. Owens and J. Fedder	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375	8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Nuclear Agency Washington, D.C. 20305	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem H02-41 DNA Project No. S99QAXHC066	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 16 S99QAXH 17 C066	12. REPORT DATE 11 Jan 1978 13. NUMBER OF PAGES 30 12 12p 15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 18 SBIE 19 AD-E000 141		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This research was sponsored by the Defense Nuclear Agency under Subtask No. S99QAXHC066, Late Time Effects, Work Unit 4, Electrostatic-Ion Plume.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aurora Magnetic mirror		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Mirroring of energetic ions and electrons between the magnetosphere and the ionosphere could by one possible mechanism for the precipitation of energetic particles necessary for the proper model- ing of the auroral plasma. This paper considers the increased trapping or detrapping of particles in the ionosphere-magnetosphere mirror system caused by an electric potential difference along the geomagnetic field. It is found that the effect of this potential difference can be quite important to the proper modeling of the high latitude auroral plasma, but is of lesser importance for the high energy Van Allen belts.		

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THE EFFECTS OF GEOMAGNETIC FIELD ALIGNED POTENTIAL DIFFERENCES ON PRECIPITATING MAGNETOSPHERIC PARTICLES

I. INTRODUCTION

The occurrence and proper modeling of the auroral plasma requires a source of energetic particles and a mechanism for their precipitation. The source of this auroral plasma is the magnetosphere, a large reservoir of energetic ions and electrons. Moreover, the effects of the mirroring of these particles between the magnetosphere and the ionosphere could be one possible mechanism for their precipitation. Therefore it is of interest to consider the mapping of certain magnetospheric regions into their corresponding ionospheric regions by tracing the geomagnetic field lines. Accordingly, the plasma sheet region of the magnetosphere maps into the high latitude region of the diffuse aurora while the Van Allen radiation belts map into the lower latitude ionosphere.

The plasma sheet is a region of ions and electrons having an isotropic Maxwellian velocity distribution at an energy of a few Kev's [1]. Particles are continually leaking out of this region to form the diffuse aurora [2,3]. Such fluxes arise from the transmission of the particles through the ends of the geomagnetic mirror that exists between the plasma sheet and the high latitude ionosphere. The Van Allen belts are another group of particles having a loss cone velocity distribution at a higher energy of a few tens of Kev's to a few Mev's [4]. Under the proper conditions, a fraction of the particles in this region can also reach the ionosphere by being transmitted through the ends of its corresponding geomagnetic mirror. Characterizing end

losses from a magnetic mirror is a familiar problem not only in auroral studies, but also in the investigation of machines for controlled thermonuclear fusion.

This paper considers the increased trapping or detrapping of particles in the ionosphere-magnetosphere mirror system caused by an electric potential difference along the geomagnetic field. This potential difference enhances or diminishes the number of precipitating particles depending on its sign and the charge of the particles. Such potential differences can arise due to the resistivity along the magnetic field to field aligned currents. These currents have been calculated in our auroral models and lead to potential differences on the order of Kev's [5]. The occurrence of a potential difference not only modulates the precipitating fluxes, but also modifies the auroral precipitation patterns and the auroral particle energies; all of which can lead to changes in the model results.

II. ENB LOSSES FOR A MAGNETIC MIRROR WITH A FIELD ALIGNED POTENTIAL

Conservation of energy for a particle of mass m and charge q in a magnetic mirroring system $B(z)$ with a potential distribution $\phi(z)$ requires that:

$$\frac{1}{2}mV_{\parallel}^2(z) + \mu B(z) + q\phi(z) = \text{constant} \quad (1)$$

where μ , the magnetic moment, is an adiabatic invariant.

$$\mu = \frac{\frac{1}{2}mV_{\perp}^2(z)}{B(z)} \quad (2)$$

If we take $z = 0$ to be the center of a step magnetic mirror and allow for a step potential well at the mirror boundary $z = M$, we have the two possible configurations shown in Figure 1. For these configurations equation (1) can be written in the form:

$$1/2 m V_{\perp}^2(z) + m V_{\parallel}^2(0) \frac{B(z)}{B(0)} + q\phi(z) = 1/2 m V^2(0) \quad (3)$$

where we have utilized the invariance of μ . For a particle to be transmitted through the mirror requires that:

$$1/2 m V_{\parallel}^2(M) > 0. \quad (4)$$

Applying equation (4) to equation (3) then yields the condition on the velocities at $z = 0$ for transmission

$$V_{\perp}^2(0) < \frac{B(0)/B(M)}{1 - B(0)/B(M)} \left[V_{\parallel}^2(0) - \frac{2q\phi(M)}{m} \right]. \quad (5)$$

Since we are only considering the $+z$ side of the magnetic step we need only consider the region where $V_{\parallel}(0) > 0$. Figure 2 displays the region of velocities at $z = 0$ that are transmitted through the mirror for the two configurations of Figure 1.

Assume a Maxwellian velocity distribution interior to the mirror

$$f = \frac{n}{\left(\frac{2}{3}\pi\right)^{3/2} V_T^3} \exp \left[-\frac{3}{2} \left(\frac{V_{\perp}^2 + V_{\parallel}^2}{V_T^2} \right) \right] \quad (6)$$

in cylindrical coordinates where n is the particle density and V_T is the thermal velocity. First consider the detrapping case where $q\phi(M) < 0$. The flux at $z = 0$ transmitted through the mirror is then:

$$F_T = \int_0^{\infty} \int_0^{V_{\perp}^2(0)} \int_0^{2\pi} \frac{n V_{\parallel}(0)}{\left(\frac{2}{3}\pi\right)^{3/2} V_T^3} \exp \left[-\frac{3}{2} \left(\frac{V_{\perp}^2(0) + V_{\parallel}^2(0)}{V_T^2} \right) \right] dV_{\perp}(0) dV_{\parallel}(0) \quad (7a)$$

where

$$V_{\perp}^2(0) = \frac{B(0)/B(M)}{1 - B(0)/B(M)} \left[V_{||}^2(0) - \frac{2q\phi(M)}{m} \right]. \quad (7b)$$

Performing the integration leads to:

$$F_T = \frac{nV_T}{\sqrt{6\pi}} \left\{ 1 - \left[1 - \frac{B(0)}{B(M)} \right] \exp \left[\frac{B(0)/B(M)}{1 - B(0)/B(M)} \frac{q\phi(M)}{kT} \right] \right\} \quad (8a)$$

where

$$\frac{1}{2} m V_T^2 = \frac{3}{2} kT. \quad (8b)$$

Now consider the trapping case where $q\phi(M) > 0$. Here the flux at $z = 0$ transmitted through the mirror is:

$$F_T = \int_{-\infty}^{\infty} \int_{\sqrt{2q\phi(M)/m}}^{V_{\perp}(0)} \int_0^{2\pi} \frac{nV_{||}(0)}{\left(\frac{2}{3}\pi\right)^{3/2} V_T^3} \exp \left\{ -\frac{3}{2} \left[\frac{V_{\perp}^2(0) + V_{||}^2(0)}{V_T^2} \right] \right\} dV_{\perp}(0) dV_{||}(0) \quad (9)$$

which yields after integration:

$$F_T = \frac{nV_T}{\sqrt{6\pi}} \frac{B(0)}{B(M)} \exp \left[-\frac{q\phi(M)}{kT} \right]. \quad (10)$$

Similarly the total flux at $z = 0$ travelling toward the mirror is

$$F = \frac{nV_T}{\sqrt{6\pi}}. \quad (11)$$

Utilizing equations (8a), (10), and (11) we can define a transmission coefficient

($T = F_T/F$) for the two cases. For the detrapping case

$$T_{\text{Detrapping}} = 1 - \left[1 - \frac{B(0)}{B(M)} \right] \exp \left[\frac{B(0)/B(M)}{1 - B(0)/B(M)} \frac{q\phi(M)}{kT} \right] \quad (12a)$$

$$\frac{q\phi(M)}{kT} < 0 \quad (12b)$$

and for the trapping case

$$T_{\text{Trapping}} = \frac{B(0)}{B(M)} \exp \left[- \frac{q\phi(M)}{kT} \right] \quad (13a)$$

$$\frac{q\phi(M)}{kT} > 0. \quad (13b)$$

In the potential free case $\left(\frac{q\phi(M)}{kT} = 0 \right)$ both equations (12a) and (13a) reduce to the familiar result

$$T = \frac{B(0)}{B(M)}. \quad (14)$$

For certain applications it is of interest to expand equation (12a) in the limit of large mirror ratio $\left(\frac{B(M)}{B(0)} \gg 1 \right)$ and/or a small potential difference $\left(-1 < \frac{q\phi(M)}{kT} < 0 \right)$. Such an expansion yields

$$T_{\text{Detrapping}} \approx \frac{B(0)}{B(M)} \left[1 - \frac{q\phi(M)}{kT} \right]. \quad (15)$$

Since for this case $\frac{q\phi(M)}{kT} < 0$, the potential produces an enhancement to the transmission coefficient for a simple magnetic mirror given by equation (14). Similarly expanding equation (13a) in the limit of a small potential difference $\left(0 < \frac{q\phi(M)}{kT} < 1 \right)$ leads to:

$$T_{\text{Trapping}} \approx \frac{B(0)}{B(M)} \left[1 - \frac{q\phi(M)}{kT} \right]. \quad (16)$$

Since for this case $\frac{q\phi(M)}{kT} > 0$, the potential produces a decrease in the transmission coefficient of equation (14).

III. DISCUSSION

The two most important equations from the preceding section are the systems (12) and (13) which prescribe the transmission coefficients for the two possible charge states and potential differences. It is important to observe that the quantity $q\phi(M)$ determines whether trapping or detrapping of particles occurs. For electrons a positive potential difference along the geomagnetic field (i.e. the ionosphere charged positive relative to the magnetosphere) produces an enhanced precipitation, while for ions a corresponding negative potential difference has the same effect. It is also relevant to note that in the absence of a field aligned potential difference more electrons will precipitate from a given charge neutral system of Maxwellian electrons and ions having equal temperatures, since the flux, equation (11), varies directly with the thermal velocity. The thermal velocities of equal temperature electrons and ions are in inverse proportion to the square root of their respective masses.

We will now present some examples of these effects for plasmas in the earth's magnetosphere. The geomagnetic mirror ratio $B(0)/B(M)$ between the plasma sheet and the high latitude ionosphere ranges between 2×10^{-2} and 5×10^{-4} [4]. The ambient plasma sheet density is approximately 1 particle/cm³ with a temperature of a few Kev's [1,4]. Therefore, in the absence of any potential difference along the magnetic field, there is a flux of precipitating electrons on the order of 5×10^8 electrons/cm²-sec and a corresponding flux of ions on the order of 10^7 ions/cm²-sec. Recent satellite observations of diffuse aurora have shown precipitating fluxes of these magnitudes [6]. Such a difference in the precipitating fluxes would usually lead to charge build up and a subsequent equalization of the fluxes. This does not occur in the ionosphere due to the presence of highly mobile ambient cold electrons, which can flow out of the ionosphere in order to neutralize the charge build up created by the high energy electron

flux. Since the plasma sheet remains essentially an isotropic Maxwellian distribution of particles, either equation (12) or (13), depending on the sign of $q\phi(M)$, will govern the precipitation in the presence of a potential difference. Our auroral models have shown that potential differences on the order of Kev's are likely to exist along the geomagnetic field lines [5]. Therefore the precipitation from the plasma sheet can vary from more than twice to less than one-half that of the potential free state.

For the Van Allen belts the geomagnetic mirror ratio is generally less than .02 and the ambient density is less than .1 particle/cm³ [4]. Since the ambient particles have a loss cone distribution at tens of Kev's to a few Mev's, there is negligible precipitation in the absence of a large potential difference or a strong pitch angle scattering mechanism. In fact only equation (15) from the preceding section has any practical application for this region, but it needs to be modified to reflect the fact that there are no particles within the loss cone,

$$\frac{v_{\perp}^2(0)}{v_{\parallel}^2(0)} < \frac{B(0)/B(M)}{1 - B(0)/B(M)}.$$

Considering this the transmission coefficient for the Van Allen belts, in the limit of a small potential difference, is given as:

$$T_{\text{Detrapping}} \approx - \frac{B(0)}{B(M)} \frac{q\phi(M)}{kT} \quad (17a)$$

$$-1 < \frac{q\phi(M)}{kT} < 0. \quad (17b)$$

From equations (11) and (17a) the precipitating flux can be calculated for any given potential difference. Such a flux is likely to be small except during very large geomagnetic disturbances.

From the preceding results, we can draw the following conclusions:

1. Enhanced or diminished particle precipitation due to field aligned potential differences is likely to be quite important to the proper modeling of the high latitude auroral plasma since

potential drops due to the strong geomagnetic field aligned currents can be sizable fractions of the electron and ion energies in the plasma sheet. As we have shown potential differences of this magnitude can lead to a large modulation of the auroral precipitation fluxes.

2. Conversely, for the high energy Van Allen belts such a mechanism is not likely to be significant since except for highly disturbed times it is very difficult to get field aligned potential differences much greater than a few Kev's; therefore the potential difference will only be a very small fraction of the particles' ambient energy.

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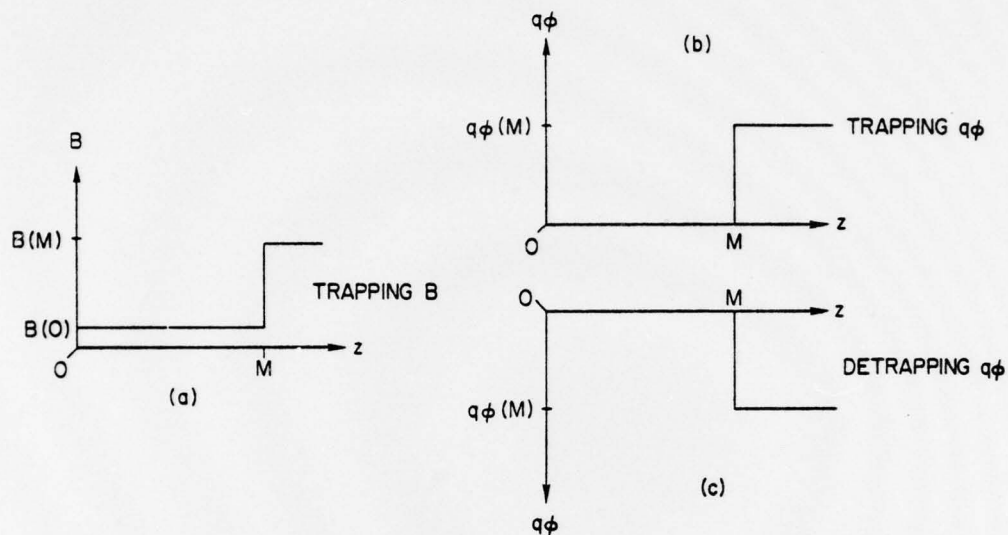


Fig. 1 - (a) A trapping step magnetic well configuration; (b) A trapping step potential well configuration where $q\phi(M) > 0$; and (c) A detrapping step potential well configuration where $q\phi(M) < 0$.

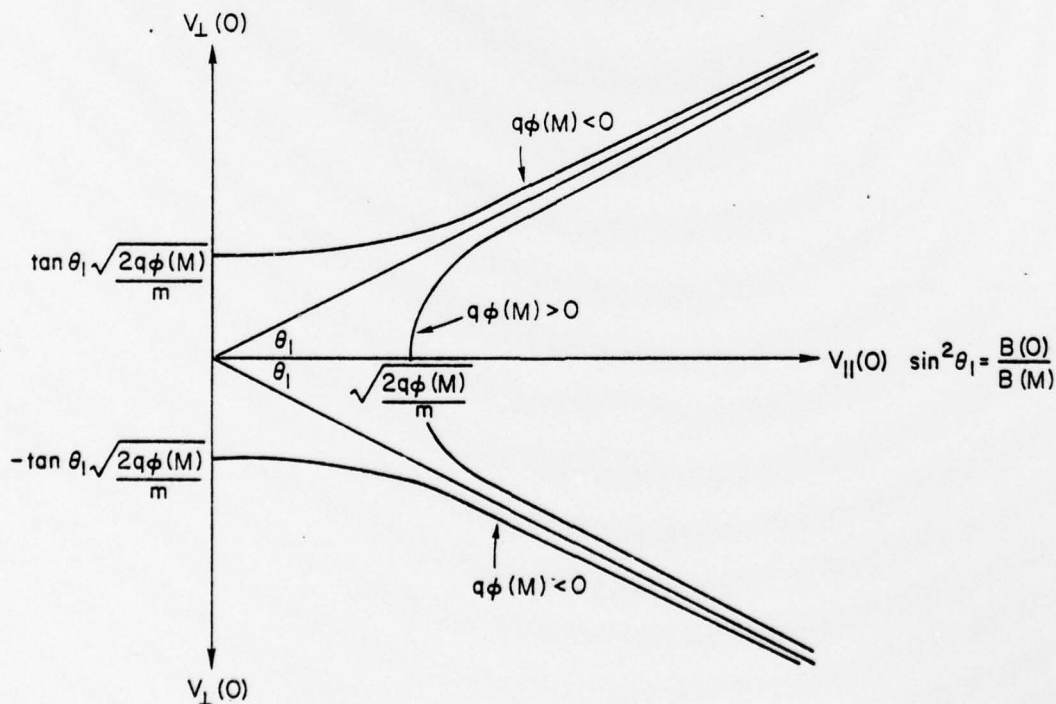


Fig. 2 - The region of velocity space at $z = 0$ that is transmitted through the mirroring system for the two potential configurations of Figure 1. The region to the right of the respective curves represents the transmitted velocity space.

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