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THE POSSIBILITY OF EXCITING ALFVÉN WAVES
BY THE SPACE SHUTTLE

by
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I. INTRODUCTION

The goal of this paper is to review the theory of Alfvén wave generation by a moving object, and to consider the prospects for generation of Alfvén waves in the ionosphere by the space shuttle. Alfvén waves were first postulated by Alfvén [1942] using the theory of magnetohydrodynamics or MHD. MHD refers to the study of highly conducting fluid in the presence of a magnetic field. In the case of an incompressible MHD fluid, Alfvén found that there is one wave mode that can propagate. This wave, often referred to as a Shear Alfvén wave, is primarily electromagnetic in nature. The wave is characterized by a perturbation magnetic field which is transverse to the undisturbed magnetic field and propagates along the direction of the undisturbed field. Also the fluid is perturbed in a direction transverse to the undisturbed magnetic field. Often, the Shear Alfvén wave is described as being analogous to a wave on a taut string, where the Maxwell stress $\frac{1}{2} \frac{B^2}{\mu_0}$ provides the tension. Herlofson [1950] and Van de Hulst [1951] first demonstrated that, if an MHD fluid is allowed to be compressible, two additional wave modes are possible: the fast and slow magnetosonic modes. These two modes have both acoustic and electromagnetic character, and are also sometimes referred to as Alfvén waves. This paper is primarily concerned with

Shear Alfvén waves, which will be referred to simply as Alfvén waves, and the other MHD modes will be referred to as magnetosonic waves.

An object moving through a plasma with a uniform magnetic field \underline{B} , in a direction transverse to \underline{B} , can generate an Alfvén wave. Associated with the wave is some system of currents. Work has been done on several examples of Alfvén waves generated by objects moving through plasma. One of the first examples described in the literature is the draping of magnetic field lines around a comet to form the comet tail [Alfvén, 1957]. The distortion of the interplanetary field by the comet represents an Alfvén wave. Drell et al. [1965] showed that a satellite moving through the ionosphere might also generate an Alfvén wave. In their paper Drell et al. develop a model for Alfvén wave generation by a satellite using linear perturbation theory. Another example, which was first predicted by Piddington and Drake [1968], occurs at Jupiter's moon Io. Io moving through Jupiter's magnetosphere produces a current system which generates an Alfvén wave. Models for Alfvén wave generation at Io have been proposed, including those of Goertz and Deift [1973], Neubauer [1980], and Goertz [1980]. The only observationally verified occurrence of an Alfvén wave generated by a moving object is at Io [Ness et al., 1979]. However, it may be possible to detect Alfvén waves excited by the space shuttle.

The Spacelab 2 mission of the space shuttle provides opportunity for in situ measurement of Alfvén waves, if they occur. During one portion of the mission, a spacecraft called the PDP (Plasma

Diagnostics Package) is released from the shuttle as a free flying satellite. When the PDP is some distance away from the space shuttle, instruments on the PDP could detect an Alfvén wave. In this paper we consider methods of detecting the occurrence of an Alfvén wave from the available instrumentation on the PDP.

II. ALFVÉN WAVES EXCITED BY A SATELLITE IN THE IONOSPHERE

In this section the model of Drell et al. [1965] for a satellite in the ionosphere is presented, followed by a discussion of practical considerations which may modify or limit results of this idealized model. Drell et al. represent the satellite as a perfect conductor and assume the satellite moves through plasma with a uniform magnetic field. The approximation of a cold plasma is made, and linear perturbation theory is applied. Further approximations appropriate to obtaining magnetohydrodynamic results are made. A wave equation for an Alfvén wave is obtained. Of course Alfvén waves can also be derived directly from the MHD equations, as will be shown in a later section.

Following the development of Drell et al., consider a perfect conductor moving in a collisionless plasma in a direction perpendicular to a uniform magnetic field \underline{B}_0 . As shown in Figure 1, the magnetic field \underline{B}_0 is in the z-direction, and the velocity \underline{V} of the object is in the x-direction. In the conductor, a motional electric field

$$\underline{E} = \underline{V} \times \underline{B} \quad (1)$$

will be just cancelled by the charge separation shown in Figure 1.

Assume that the conductor has no work function to prevent the flow of

electrons from the conductor's surface into the plasma. Also, note that for a collisionless plasma the conductivity parallel to \underline{B} is large, and the conductivity perpendicular to \underline{B} is small. It will be shown that the model of Drell et al. is consistent with the physical situation represented in Figure 2. That is, current is driven by the motional electric field in the conductor and flows in Alfvén wings. The angle of the wings is given by $\alpha = \tan^{-1} V/V_a$ where $V_a = \sqrt{B^2/\mu_0\rho}$ is the local Alfvén speed.

The dielectric character of the plasma is represented by

$$\underline{D} = \underline{\epsilon} \underline{E}$$

$$\text{or } \underline{D} = \epsilon_0 \underline{K} \underline{E} \quad (2)$$

From cold plasma theory the dielectric tensor \underline{K} is given by

$$\underline{K} = \begin{bmatrix} 1 - \sum_s \frac{\omega_{ps}^2}{(\omega^2 - \omega_{gs}^2)} & -i \sum_s \frac{\omega_{gs} \omega_{ps}^2}{\omega(\omega^2 - \omega_{gs}^2)} & 0 \\ i \sum_s \frac{\omega_{gs} \omega_{ps}^2}{(\omega^2 - \omega_{gs}^2)} & 1 - \sum_s \frac{\omega_{ps}^2}{(\omega^2 - \omega_{gs}^2)} & 0 \\ 0 & 0 & 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \end{bmatrix} \quad (3)$$

where ω_{ps} is the plasma frequency and ω_{gs} is the gyrofrequency of species s .

An approximation must be made to obtain results of a magneto-hydrodynamic nature. That is, we desire a fluid-type solution, implying that we are concerned with oscillations involving bulk motion of the plasma. The time scale for fluid motion should be longer than the ion gyroperiod, or equivalently, one should have $\omega \ll \omega_{gi}$. Long time scales are required, because for time scales shorter than the ion gyroperiod, i.e., $\omega \gg \omega_{gi}$, the electrons and ions behave differently so that a single fluid theory is not appropriate. Making the low frequency approximation, and assuming one ion species, one can obtain:

$$\underline{K} = \begin{bmatrix} 1 + \frac{c^2}{v_a^2} & 0 & 0 \\ 0 & 1 + \frac{c^2}{v_a^2} & 0 \\ 0 & 0 & 1 - \frac{\omega_p^2}{\omega^2} \end{bmatrix} \quad (4)$$

The conductivity tensor is related to \underline{K} by

$$\underline{K} = \underline{1} - \underline{\sigma}/i\omega\epsilon_0 \quad (5)$$

so that

$$\underline{\sigma} = \begin{bmatrix} i\omega\epsilon_0 \frac{c^2}{v_a^2} & 0 & 0 \\ 0 & i\omega\epsilon_0 \frac{c^2}{v_a^2} & 0 \\ 0 & 0 & -i\omega\epsilon_0 \frac{\omega_p^2}{\omega^2} \end{bmatrix} \quad (6)$$

or,

$$\underline{\sigma} = \begin{bmatrix} \sigma_{\perp} & 0 & 0 \\ 0 & \sigma_{\perp} & 0 \\ 0 & 0 & \sigma_{\parallel} \end{bmatrix} \quad (7)$$

The requirement that $\sigma_{\parallel}/\sigma_{\perp} \gg 1$ then becomes $\omega^2 \ll \left(\frac{\omega_p^2 v_a^2}{c^2}\right)$, which is consistent with the low frequency assumption made.

In order to obtain equations for MHD waves, we next consider Maxwell's equations with the expression for \underline{K} from Equation 4. Also the field strengths are linearized by setting $\underline{B} = \underline{B}_0 + \underline{B}_1$, where \underline{B}_0 is the undisturbed uniform magnetic field, and setting $\underline{E} = \underline{E}_1$. Source terms $\rho(\underline{r}, t)$ and $\underline{J}(\underline{r}, t)$, external to the plasma, are assumed. For the present, $\rho(\underline{r}, t)$ is left completely general, but $\underline{J}(\underline{r}, t) = \underline{J}(x-Vt, y, z)$. That is, the source current is the current through the moving conductor, and thus the current must depend on $(x-Vt)$. Maxwell's equations then, in Fourier transformed form, are the following:

$$\begin{aligned}
\underline{k} \times \underline{E}_1 &= i\omega \underline{B} \quad , \\
\underline{k} \times \underline{B}_1 &= \mu_0 \underline{J}(\underline{k}, \omega) + \mu_0(-i\omega) \underline{D} \quad , \\
\underline{k} \cdot \underline{D}_1 &= \rho(\underline{k}, \omega) \quad , \\
\underline{k} \cdot \underline{B}_1 &= 0 \quad ,
\end{aligned}
\tag{8}$$

where

$$\underline{J}(\underline{k}, \omega) = \underline{J}(\underline{k}) \delta(\omega - \underline{k} \cdot \underline{V}) \quad . \tag{9}$$

Define

$$\begin{aligned}
\varepsilon_{\perp} &= \varepsilon_0(1 + c^2/V_a^2) \\
\varepsilon_{\parallel} &= \varepsilon_0(1 - \omega_p^2/\omega^2)
\end{aligned}
\tag{10}$$

and

$$\underline{E}_1 = \underline{E}_1^{\ell} + \underline{E}_1^{tr} \tag{11}$$

where

$$\underline{k}_{\perp} \cdot \underline{E}_1 = k_{\perp} E_1^{\ell} \tag{12}$$

and

$$\underline{k}_\perp \times \underline{E}_\perp = k_\perp \times \underline{E}_\perp^{\text{tr}} \quad . \quad (13)$$

The following forms can be obtained.

$$(\omega^2 \mu_0 \epsilon_\perp - k_\parallel^2 - k_\perp^2 \frac{\epsilon_\perp}{\epsilon_\parallel}) E_\perp = \frac{\mu_0 \omega}{i} \frac{\underline{J} \cdot \underline{k}_\perp}{k} \delta(\omega - \underline{k} \cdot \underline{V}) - \frac{k_\perp \rho}{i \epsilon_\parallel} \quad (14)$$

$$(\omega^2 \mu_0 \epsilon_\perp - k_\parallel^2 - k_\perp^2) E_\perp^{\text{tr}} = \frac{\mu_0 \omega}{i} \frac{|\underline{J} \times \underline{k}_\perp|}{k_\perp} \delta(\omega - \underline{k} \cdot \underline{V}) \quad (15)$$

Equation 14 represents the Alfvén wave. For $\epsilon_\perp/\epsilon_\parallel \ll 1$, the equation reduces to a one-dimensional equation for a transverse electric field propagating along the \underline{B}_0 direction with velocity $\approx V_a$ and frequency $\omega = \underline{k} \cdot \underline{V}$. The wavelength parallel to \underline{V} is $\sim L$, the length of the conductor along the direction of motion, so that $\omega \sim 2\pi V/L$. Equation 15 represents an magnetosonic wave, also with velocity $\approx V_a$. But this wave propagates isotropically, and thus the energy falls away as $1/r^2$. In contrast, the Alfvén wave energy is concentrated along one direction. So the Alfvén wave is more important, and the magnetosonic wave is not considered here.

Examining the wave equation for the Alfvén waves, it is possible to characterize the wave produced by the moving conductor. First Equation 14 is transformed back to real space:

$$\left[-\frac{1}{V_a^2} \frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial z^2} \right] \nabla_{\perp} \cdot \underline{E} = \mu_0 \frac{\partial}{\partial t} \nabla_{\perp} \cdot \underline{J}(x-Vt, y, z) \quad . \quad (16)$$

It follows from this form of the equation that the wave field \underline{E}_1 , is a function of the variables

$$y, x-Vt \pm \left(\frac{V}{V_a} \right) z$$

and therefore \underline{B} is a function of the same variables. Thus, as stated earlier, the perturbation fields occur in Alfvén wings which are at an angle $\alpha = \tan^{-1} V/V_a$ to the direction of \underline{B}_0 . Since the tangential component of the electric field \underline{E} is continuous across the surface of the conductor, the electric field between the wings has the same magnitude as that in the conductor: $-(\underline{V} \times \underline{B}_0)$. From Equation 8, it can be determined that the magnitude of the perturbation magnetic field is $\underline{B}_1 = (V/V_a) \underline{B}_0$. Thus, the linear theory is valid when $M_a \ll 1$. The plasma in the wings will experience an $\underline{E} \times \underline{B}$ drift that will approach the velocity of the conductor, \underline{V} . That is, the plasma between the wings will move with the conductor.

From the model being presented, Drell et al. also obtain expressions for the power radiated by Alfvén waves, the total current flow, and the wing surface charge density. Consider for now the conductor to be a rectangularly shaped box with dimensions L along the

x-direction, W along the y-direction, and D along the z-direction. The surface area of radiation is then W x L, and the power radiated is

$$P = \frac{V_o^2 B_o^2}{V_a} WL \quad . \quad (17)$$

The potential drop across the conductor is E x W, so that the current is

$$I = \frac{P}{EW} = \frac{V_o}{V_a} B_o L \quad . \quad (18)$$

From Gauss' law, the surface charge on the wing is

$$\sigma = \epsilon_L E = \epsilon_o \frac{c^2}{V_a^2} V B_o \quad . \quad (19)$$

The model that has been presented is quite idealized. Some practical considerations which modify or limit the results of the model should be considered. For example, the separation between the current wings should be more than 2 ion gyroradii. If the velocity of the ion is given by $V = \omega_{gi} r$, with r being the ion gyroradius, then

$$W \geq \frac{2V}{\omega_{gi}} \quad (20)$$

where recall that W is the width of the object in the y -direction. Thus, an object must be of a minimum width in the y -direction to generate Alfvén waves. Another practical consideration is that of collisions. Including collision effects would modify the expressions for $\underline{\epsilon}$, thus changing the expression for $\underline{\sigma}$. This may result in a situation where the assumption that $\sigma_{\perp}/\sigma_{\parallel} \ll 1$ is no longer a good one. In this case, one expects the current wings will no longer have negligible thickness, but will broaden in the x and y directions.

Some further considerations involve limitations on the current flow. The current in the wings will be carried primarily by electrons, since they have greater mobility than the ions. In one wing electrons are drawn into the conductor, neutralizing the net positive charge there. In the other wing, electrons must overcome the work function to leave the conductor. Photoelectric emission from the satellite surface may then be important in achieving the needed current flow. Also of concern is the conductivity of the object. The model of Drell et al. has been worked out for an ideal conductor. However, in the case of an object with finite conductivity, the charge separation in the object might not be maintained, so that the electric field, and thus the current, would be reduced. The issue of the conductivity of the moving object will be considered in more detail with reference to the I_0 problem in the next section.

III. ALFVÉN WAVE GENERATION BY IO

Jupiter's moon Io generates an Alfvén wave as it moves through Jupiter's magnetosphere. In fact, the only observationally verified case of Alfvén wave generation by a moving object occurs at Io. Typical parameters for conditions at Io appear in Table 1. Figure 3 shows data from the magnetometer on Voyager 1 [Ness et al., 1979]. Depicted in the figure is the perturbation magnetic field vector along the Voyager 1 trajectory as the spacecraft passed through the Io flux tube. The background magnetic field is along the z-axis, or perpendicular to the page. A significant perturbation of the magnetic field was measured in the region of the Io flux tube, indicating the presence of an Alfvén wave.

In this section, we will discuss some aspects of the models for Io of Goertz and Deift [1973], and of Neubauer [1980]. In contrast to the model of Drell et al., these two models are obtained directly from MHD theory. Recall that the model of Drell et al. was introduced through cold plasma theory. The model of Goertz and Deift demonstrates the nature of the plasma flow around Io. The model of Neubauer treats the problem without making the linear approximation. Both models compliment the model already discussed of Drell et al. for a satellite in the ionosphere, and should provide further insight into the situation at the shuttle. The conditions at Io relevant

to Alfvén wave production are considered, and the theory of ion pickup is introduced.

Goertz and Deift [1973] model Io as a spherical object moving in a magnetic field. Their development demonstrates that the plasma flows around Io and around the current wings. Note that plasma flow should be similar for the satellite in the ionosphere. The nature of the plasma flow was not brought out by the model of Drell et al. Goertz and Deift also consider the effect of the conductivity of both the object and the medium the object moves through.

Following the development of Goertz and Deift, consider a perfectly conducting spherical object moving through a uniform magnetic field. In the reference frame of the object, the object appears to be immersed in a uniform electric field. A charge separation is produced which cancels the electric field inside the conductor, but produces an electrostatic dipole field outside the conductor, as shown in Figure 4. Next, suppose that the object has conductivity σ_o and the outside medium has conductivity σ_m . Expressions for the potentials inside the object ϕ_o and in the medium ϕ_m are given by:

$$\begin{aligned}\phi_o &= \frac{\sigma_o}{\sigma_o + 2\sigma_m} V B_o r \cos \theta \\ \phi_m &= \frac{\sigma_o}{\sigma_o + 2\sigma_m} V B_o \frac{R_o^3}{r^2} \cos \theta\end{aligned}\tag{21}$$

where θ , r , and R_0 are shown in Figure 5. From the reference frame of the object, the electric field in the medium is given by

$$\underline{E}_m = -\nabla\phi_m + \underline{V} \times \underline{B}_0 \quad . \quad (22)$$

This reduces to a dipole field when $\sigma_m = 0$. The larger σ_m , the smaller the electric field outside.

For ideal MHD, plasma has a flow velocity $(\underline{E} \times \underline{B})/B^2$. Since there is an electric field outside the object, the plasma flow is deflected around the object. If the object is a perfect conductor, then the plasma flows completely around the object, as shown in Figure 6. If the object is not a perfect conductor then the $\underline{E} \times \underline{B}$ drift is reduced, and plasma impinges on the object as shown in Figure 7. If $\sigma_0 \gg \sigma_m$ then the internal electric field is small, and there will be little current through the object. A large current is necessary for Alfvén wave generation.

Just as the plasma flows around the object, it will also flow around the current wings. The wings carry surface charge, and thus there is an electric field outside the wings. Plasma then $\underline{E} \times \underline{B}$ drifts around the wings as shown in Figure 8.

Wave expressions were obtained previously from the cold plasma model of Drell et al. Similar wave expressions are obtained rather easily from basic MHD relations as is shown by Goertz and Deift. As before, let the zeroth order magnetic field be in the z -direction,

and the velocity be along the x-direction. For an ideal MHD fluid, $\underline{E} = -\underline{U} \times \underline{B}$ where \underline{U} is the flow velocity. \underline{E} and \underline{U} are first order quantities. Faraday's law yields:

$$\frac{\partial \underline{B}}{\partial t} = -\nabla \times \underline{E} = \nabla \times (\underline{U} \times \underline{B}) \quad (23)$$

$$\frac{\partial B_x}{\partial t} = B_0 \frac{\partial}{\partial z} U_x$$

From the momentum equation, one obtains

$$\rho \frac{\partial \underline{U}}{\partial t} = \underline{J} \times \underline{B} = \frac{(\nabla \times \underline{B}) \times \underline{B}}{\mu_0} \quad (24)$$

$$\rho \frac{\partial U_x}{\partial t} = \frac{B_0}{\mu_0} \left(\frac{\partial}{\partial z} B_x \right)$$

Combining Equations 23 and 24 one obtains

$$\frac{\partial^2 B_x}{\partial z^2} - \frac{1}{V_a^2} \frac{\partial^2 B_x}{\partial t^2} = 0 \quad (25)$$

$$\frac{\partial^2 U_x}{\partial z^2} - \frac{1}{V_a^2} \frac{\partial^2 U_x}{\partial t^2} = 0 \quad (26)$$

As in the model of Drell et al., the result is a perturbation that propagates with speed V_a .

Neubauer's model for I_0 essentially extends the model of Drell et al. for the satellite by deriving the electric and magnetic field expressions without resorting to linear approximation. Also, flow which is not perpendicular to the background magnetic field is included in Neubauer's model. An assumption is made, however, that the solutions will be similar to the linear solution in the following way. Solutions for the perturbed quantities are assumed to be constant along the direction

$$\underline{V} \pm \underline{B}_0 / (\mu_0 \rho)^{1/2}$$

where \underline{V} is the unperturbed flow velocity, and \underline{B}_0 is the unperturbed magnetic field.

Neubauer obtains a relation between the current and the electric field. Consider the coordinates shown in Figure 9. The angle θ_A is given by

$$\sin \theta_A = \frac{M_A \cos \theta}{(1 + M_A^2 + 2M_A \sin \theta)^{1/2}} \quad (27)$$

where M_A is the Alfvén mach number. The current along the z-direction is related to the electric field:

$$\nabla \cdot \underline{E} = (\underline{V} + \underline{B}_0 / (\mu_0 \rho)^{1/2}) \cdot \underline{J} \mu_0 \quad (28)$$

$$J_z = \frac{\nabla \cdot \underline{E}}{\mu_0 V_a (1 + M_A^2 + 2M_A \sin \theta)^{1/2}}$$

The term

$$\Sigma_A = \frac{1}{\mu_0 V_a (1 + M_A^2 + 2M_A \sin \theta)^{1/2}} \quad (29)$$

acts as a conductance for the system in the z-direction. Neubauer suggests that this conductance will "close" the current circuit for currents generated in a moving satellite, such as Io. That is, theoretically, the currents can be allowed to have infinite extent. In a real situation, current closure will occur. For example, at Io the Alfvén waves are thought to propagate to the jovian ionosphere, where a reflection can occur, and currents are closed in that process.

The two models discussed in this section treat Io in the same manner: as a solid conductor. This is a poor approximation because Io is actually surrounded by a neutral atmosphere and an ionosphere. The $\underline{V} \times \underline{B}$ electric field might drive current through Io's ionosphere rather than through the body of the moon. But more important than the current driven by the $\underline{V} \times \underline{B}$ electric field is the current due to a process called ion pickup [Goertz, 1980].

The ion pickup process occurs in the following manner. A neutral particle from Io's atmosphere is ionized, possibly by collision with a magnetospheric electron. Io's atmosphere is mostly SO_2 , which dissociates and ionizes, forming S^+ and O^+ . In the reference frame of Io, the newly formed electron and ion pair see both an \underline{E} and \underline{B} field. They both begin a cycloid motion with guiding center velocity $\underline{V}_g = (\underline{E} \times \underline{B})/B^2$. The ion guiding center is displaced one gyroradius in the direction of \underline{E} , and the electron guiding center is displaced one gyroradius in the direction opposite to \underline{E} . Both particles are picked up by the plasma that streams by Io. But more importantly for Alfvén wave generation, the particle motions produce a net current in the direction of \underline{E} . That is, the pickup process acts to extract energy from the flow and produce an effective emf. Thus ion pickup, by enhancing the perpendicular current through Io's atmosphere, can help drive the current wings described earlier.

The pickup process is also referred to as mass loading for the following reason. Momentum imparted to the newly formed ion must be extracted from the incident flow, resulting in a deceleration of the flow. Further, nonionizing collisions between plasma particles and neutrals near the Io might also impede the plasma flow. Since the magnetic field is frozen in the plasma, this effect distorts the field. This effect could cause the Alfvén wave to have an angle greater than $\alpha = \tan^{-1} V/V_a$ to the unperturbed magnetic field.

For Io, the current due to ion pickup is more important than the current driven through the ionosphere by the $\underline{V} \times \underline{B}$ electric field.

To drive a large ionospheric current, without ion pickup, a large conductivity perpendicular to the magnetic field, called the Pederson conductivity, is needed. A large Pederson conductivity requires a dense neutral atmosphere, so that the plasma is collisional and the particles are not locked onto field lines. However, there is evidence that the atmosphere of Io is not dense enough to provide a large Pederson conductivity. So the current wings must be driven by the pickup current [Goertz, 1980].

Another consequence of Io not having perfect conductivity is that plasma does not flow completely around the moon. Some plasma impinges Io, as predicted by the model of Goertz and Deift [1973]. In fact, it is observed that Io absorbs particles from the incident flow [Thomsen, 1979].

Since an Alfvén wave is known to occur at Io, it is worthwhile to look at how well Io fits all the assumptions made in the theory. Several assumptions have not yet been considered. For example, low frequency is assumed in the theory. Approximating ω by $2\pi V/L$, one obtains $\omega \approx 0.20$ rad/s. This frequency is much less than the gyrofrequency for S^+ , 5.7 rad/s [see Table 1]. Also required by theory is that the width of Io be more than 2 ion gyroradii. Taking ω_{gi} for S^+ , $2V/\omega_{gi} = 19.9$ km, which is much less than Io's radius, 1820 km [see Table 1]. Recall that the linear theory is applicable when $M_a \ll 1$. For Io, because $M_a \approx 0.16$, it is preferable to not make the linear approximation. But conditions at Io fulfill the requirements

for the occurrence of Alfvén waves, and their observation is consistent with the theory.

IV. POSSIBILITIES FOR EXCITING ALFVÉN WAVES BY THE SHUTTLE

The shuttle travelling through the ionosphere may be analogous in many respects to Io moving through Jupiter's magnetosphere. An Alfvén wave might be generated by the shuttle, just as one is generated by Io. In this section we consider whether or not the requirements for generating an Alfvén wave are met by the shuttle. Typical plasma parameters and shuttle orbiter parameters for the Spacelab 2 mission are listed in Table 2.

Consider some of the assumptions of the theory. Recall that for the linear theory to be valid, $B_1/B_0 = M_a \ll 1$ is required. The Alfvén mach number M_a for the shuttle is of the order 5×10^{-2} , which is certainly small enough to apply the linear theory. Also, the MHD approximation must be valid, which implies that the plasma must be collisionless. The shuttle orbit lies mostly in the F-region of the ionosphere where collision frequencies are small compared to gyrofrequencies for both electrons and ions. So the collisionless assumption is a good one. MHD also requires that $\omega \ll \omega_{gi}$. If ω is estimated as $2\pi V/L$, where L is the length along the direction of motion, then we have $L \gg 2\pi V/\omega_{gi}$, and using values from Table 2 we obtain $L > 160\text{m}$. This result is discouraging, since the shuttle dimensions are much less than this [see Table 2]. Either the low frequency

approximation is not valid because the shuttle is too small, or the expression for ω is a poor approximation.

Consider further the importance of the shuttle dimensions in determining whether or not an Alfvén wave can be generated. Recall that the length in the $\underline{V} \times \underline{B}$ direction must be greater than 2 ion gyroradii. Also, the power radiated by Alfvén waves, according to Equation 17 is proportional to the length in the $\underline{V} \times \underline{B}$ direction times the length along the direction of motion. However, this is not quite true if the moving object is much longer in the $\underline{V} \times \underline{B}$ direction than along the direction of motion, such as in the proposed tethered satellite experiment. Rasmussen et al. [1985] point out that in such a case the fringing of the electric field becomes important and the wave amplitude is reduced. But the shuttle without a tether should not have excessive length in the $\underline{V} \times \underline{B}$ direction. From Table 2, the shuttle is 37m long with wingspan 24m. However, all surfaces except the main engine fairings are covered by insulating material. Thus, the length of the actual conducting surface may be less than 10m. The ion gyroradius for thermal O^+ , which is the dominant ion in the F-region, is of the order of 3m. So assuming that the current will flow through the body of the shuttle, the requirement that the length be more than two gyroradii might be just barely met.

Though the physical dimensions of the shuttle are important, the immediate environment around the shuttle may be of more importance in possible Alfvén wave generation. The plasma environment around the shuttle as characterized by Shawhan et al. [1984] and Murphy et al.

[1983] is described here. The shuttle is probably surrounded by neutral gas and plasma clouds, of higher density than the ambient ionosphere. The shuttle introduces neutral gas into the ionosphere locally through outgassing, dumping of water, and thruster firings. The neutral gas pressure can be enhanced by up to 2 orders of magnitude over the ambient values. The neutral gas then interacts with the local plasma and modifies it. In addition to the ambient ionospheric ions O^+ and NO^+ , H_2O^+ is found to occur near the shuttle. The H_2O^+ could be from reactions between H_2O and the O^+ present, or it could be that H_2O is ionized in some other manner. NO^+ density is found to be enhanced over natural density levels. Also, electron density higher than ambient density can be detected at times. The neutral gas and plasma clouds around the orbiter, rather than the physical size of the orbiter, may determine the possible Alfvén wave production. The plasma cloud could provide the necessary conduction path for perpendicular currents. Or neutrals could be ionized and a pickup current produced. Unfortunately, the size of the clouds is unknown.

Ion pickup might occur at the shuttle by ionization of H_2O , for example. The gyroradius for H_2O^+ in this case is approximately 17m. So, if pickup were occurring, the shuttle appears to be a conductor of length at least 17m in a direction perpendicular to the direction of motion. Also, mass loading would increase the angle of the current wings. For the shuttle, $\tan^{-1}(V/V_a)$ is of the order of 3° .

Recall from the model of Goertz and Deift that for wave generation, it is unfavorable to have σ_m , the conductivity in the ambient plasma, much less than σ_0 , the conductivity of the moving object. Due to the higher neutral pressure, the plasma around the shuttle may be slightly more collisional than the ambient, leading to $\sigma_m > \sigma_0$, so wave generation is not inhibited.

V. DETECTION OF ALFVÉN WAVES WITH THE SPACELAB 2 PDP

The Spacelab 2 mission of the space shuttle provides an opportunity to attempt to detect an Alfvén wave excited by a large object moving through the earth's ionosphere. During the mission, the PDP is released as a free flying satellite for about 6 hours. The space shuttle orbiter performs maneuvers around the PDP so that it is alternately in the ram and wake regions. Two complete orbits of the shuttle around the PDP are performed, as shown in Figure 10, and twice during each orbit a magnetic flux tube connection between the 2 objects is attained. The separation distance between the shuttle and the PDP will be approximately 150m at that time. During 2 of the flux tube crossings, an electron gun on the shuttle is fired. During the remaining 2 flux tube crossings attempts can be made to detect the possible Alfvén wave.

To detect an Alfvén wave one might first look at magnetometer data. The Alfvén disturbance at Io was detected by the magnetometer of Voyager 1 during the time the spacecraft passed through the Io flux tube [Ness et al., 1979]. A significant change in the magnetic field direction was observed. The change in field direction at the shuttle, however, will be relatively small. Recall that the perturbation magnetic field is of the order of $M_a \times B_0$. At the shuttle, this

may about 2.5×10^{-2} gauss, which is close to the magnetometer sensitivity: $\pm 1.2 \times 10^{-2}$ gauss. Thus, it may be difficult to detect an Alfvén disturbance with the PDP magnetometer. Data from additional PDP instruments should be looked at.

An Alfvén disturbance should be recognizable in electric field measurements. An instrument on the PDP measures the static electric field by measuring the potential across a dipole antenna with an antenna sphere separation of 3.89m. When the PDP is well away from the flux tube connected to the shuttle, and not in the wake region, the DC electric field instrument should see the constant $\underline{V} \times \underline{B}$ electric field. This field should have magnitude of around 0.2 to 0.4 volts/m. When the PDP enters the flux tube, passing between the current wings if present, the electric field signal will drop to nearly zero. After passing through the flux tube, the instrument should again see a field of magnitude $\underline{V} \times \underline{B}$.

If the change in the electric field signal is well defined and localized in space, then it might be possible to determine the angle between the point where the change occurs and that where the PDP would have been aligned with the undisturbed magnetic field (see Figure 11). This angle should be $\alpha = \tan^{-1} V/V_a$, unless mass loading makes it larger.

As the PDP passes through the region between the current wings, the change in plasma flow velocity should be detectable. Three particle detecting instruments on PDP, the low energy electron and proton differential energy analyzer, the retarding potential

analyzer, and the differential ion flux probe, all can detect the apparent ion beam when pointed into the ram. Between the current wings, streaming ions will not be detected when the instrument is pointed into the ram direction.

VI. CONCLUSION

Alfvén waves can be generated by a conducting object moving through a magnetized plasma. An example occurs at Jupiter's moon, Io. The space shuttle moving through the ionosphere is in many ways analogous to Io moving through the magnetosphere of Jupiter. And the space shuttle satisfies most of the requirements of the theory for Alfvén wave generation by a moving object. However, the shuttle may be too small a conductor to satisfy the theory. It is as yet unclear how to view the shuttle's conducting properties in relation to this issue. It is likely that the size of the enhanced neutral gas cloud around the shuttle is of more importance than the size of the orbiter itself. Pickup current, or current driven through an enhanced plasma cloud around the shuttle is probably more important than current through the orbiter body. So Alfvén wave generation at the space shuttle remains a possibility. Detection of the Alfvén wave using the Spacelab 2 PDP would best be accomplished with electric field and particle measurements. An object in the ionosphere larger than the shuttle would satisfy all of the requirements of the theory for Alfvén wave generation. Thus, the proposed space station, a much larger object, should generate an Alfvén wave.

Table 1
Plasma Parameters at Io

magnetospheric density near Io n_e , cm^{-3}	1500	*
Io radius R, km	1820	*
Io velocity V, km/s	56.8	*
magnetic field B_0 , nT	1900	*
Alfvén velocity V_a , km/s	356	*
Alfvén mach number M_a	0.16	*
density of Io ionosphere n_e , cm^{-3}	6×10^4	**
magnetospheric electron temperature near Io, eV	1 - 40	***
magnetospheric ion temperature near Io, eV	1 - 50	***
gyrofrequency S^+ , rad/s	5.7	
gyrofrequency O^+ , rad/s	11.4	
larmor radius pickup S^+ , km	9.97	
larmor radius pickup O^+ , km	4.98	

* Neubauer [1980]

** Strobel and Altreya [1983]

*** Belcher [1983]

Table 2
Ionospheric Plasma Parameters and Shuttle Orbiter Parameters

electron density, cm^{-3}	$10^5 - 10^6$
electron temperature, eV	0.09 - 0.26
ion temperature, eV	0.05 - 0.10
electron thermal velocity, m/s	$1.7 \times 10^5 - 3.0 \times 10^5$
ion thermal velocity (O^+), m/s	$0.7 \times 10^3 - 1.0 \times 10^3$
magnetic field, gauss	0.25 - 0.50
ion gyrofrequency (O^+), rad/s	150 - 300
ion gyroradius, m	3
Alfvén velocity V_a , km/s	96 - 610
shuttle altitude, km	310
shuttle velocity, km/s	7.7
Alfvén mach number M_a	5×10^{-2}
shuttle length, m	37
shuttle wingspan, m	24

Figure 1. Coordinate axes are shown for an ideal conductor moving through a plasma in a direction perpendicular to the magnetic field. Charge separation occurs in the conductor.

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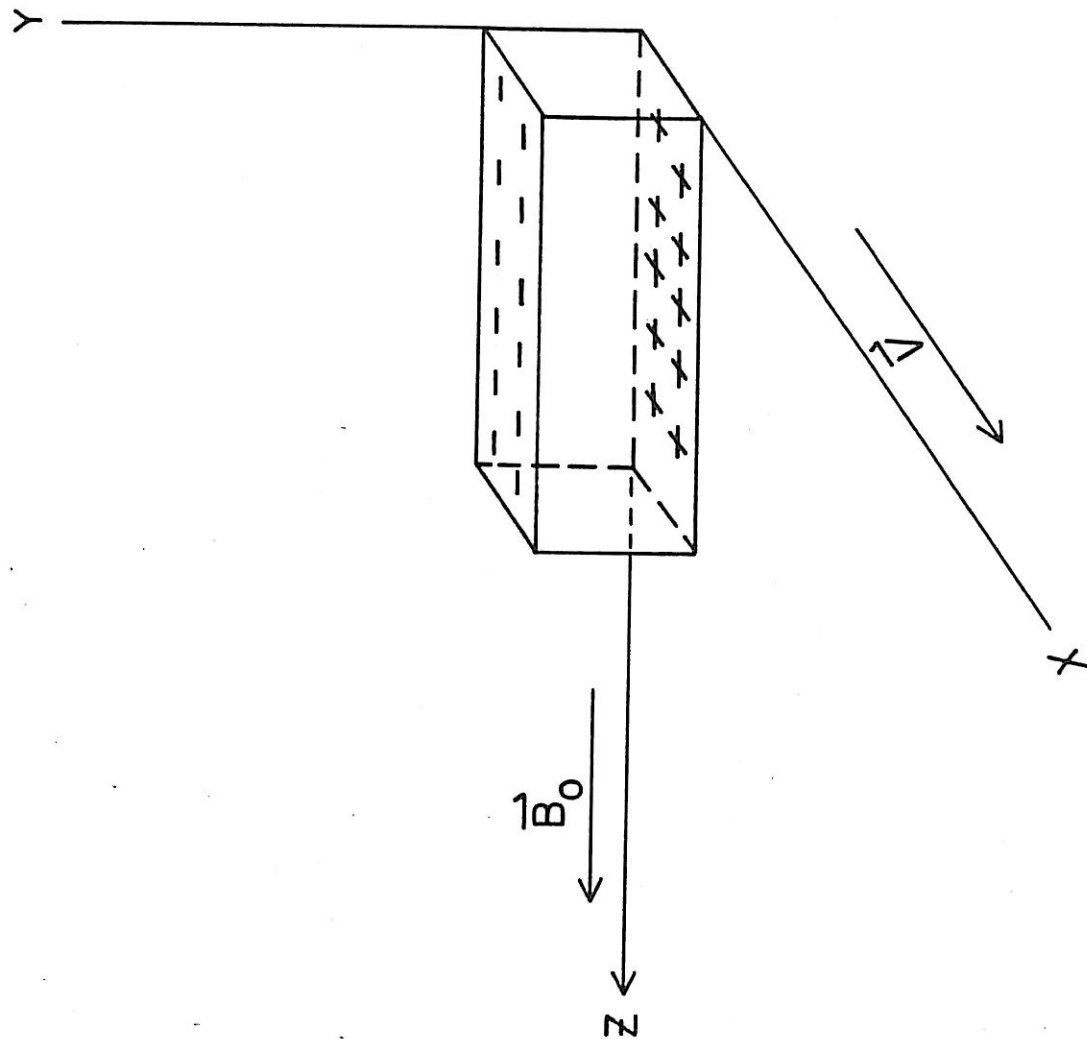


Figure 2. Current wings generated by the moving conductor.

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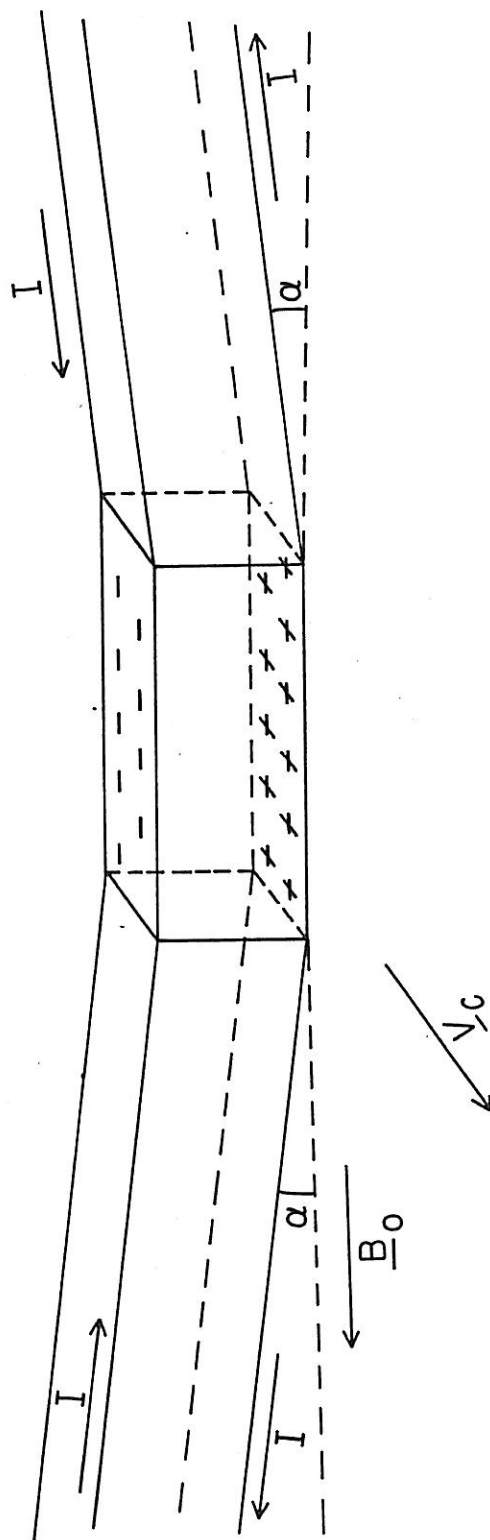


Figure 3. The perturbation magnetic field vector measured by the Voyager spacecraft as it passed through the Io flux tube. The background field is along the z-axis, or perpendicular to the page [Ness et al., 1979].

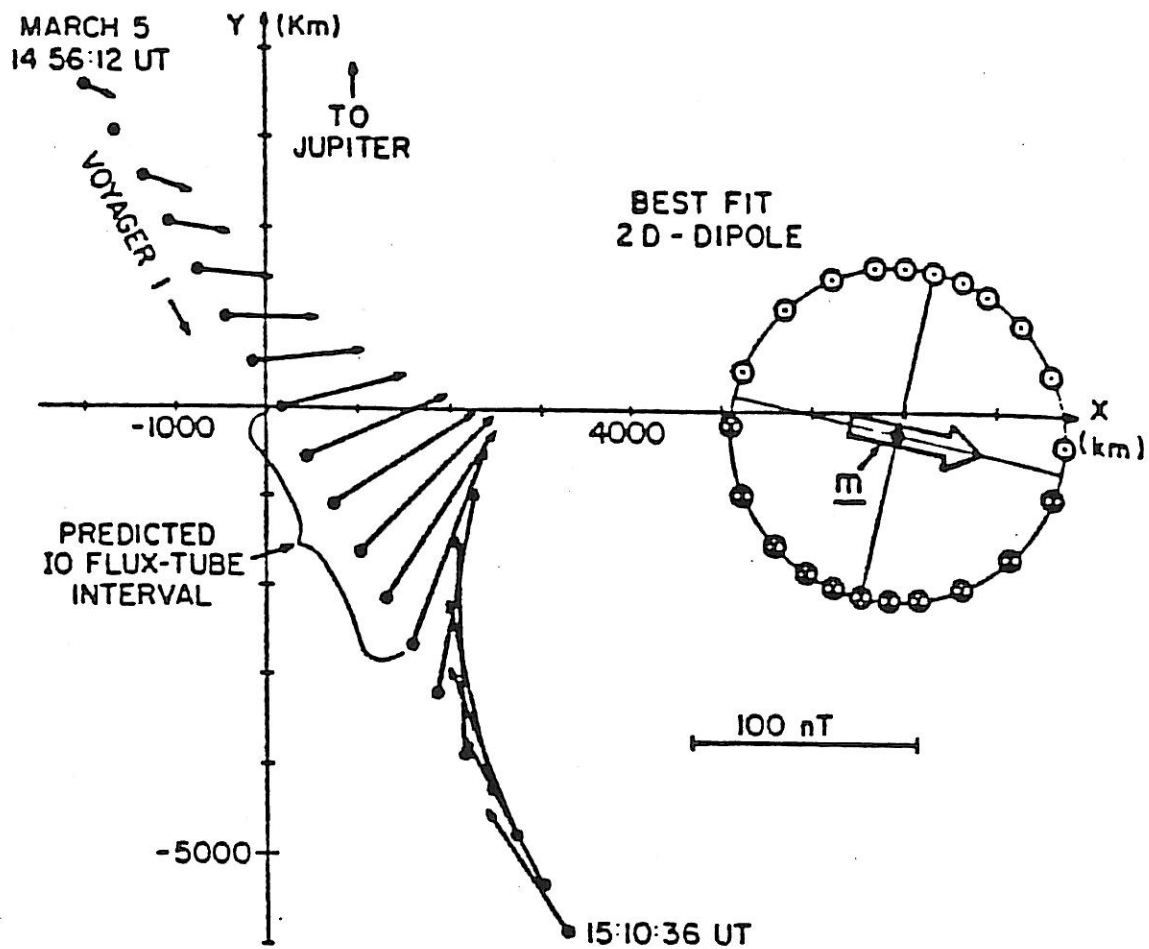


Figure 4. Conducting sphere moving in a uniform magnetic field. A charge separation is produced. The electric field outside the sphere is a dipole field.

B - G85 - 585

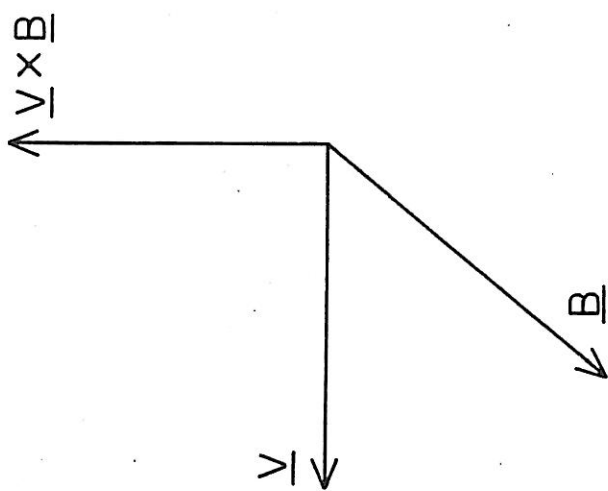
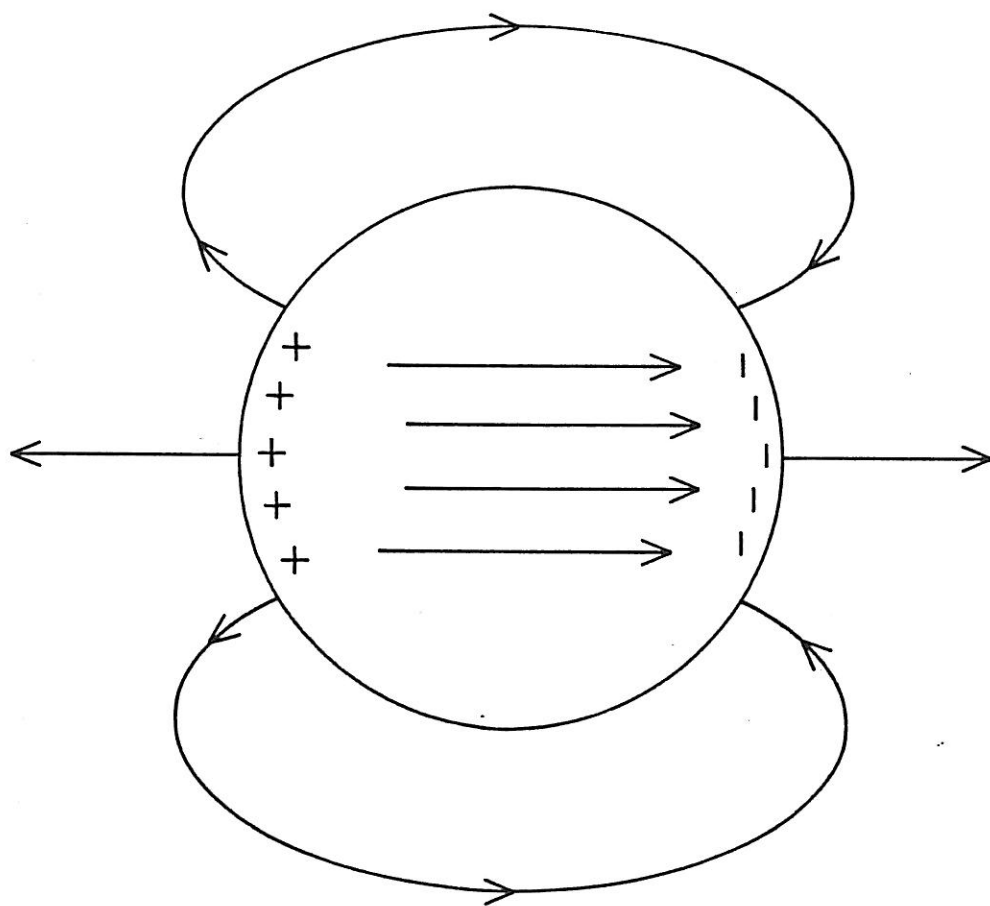
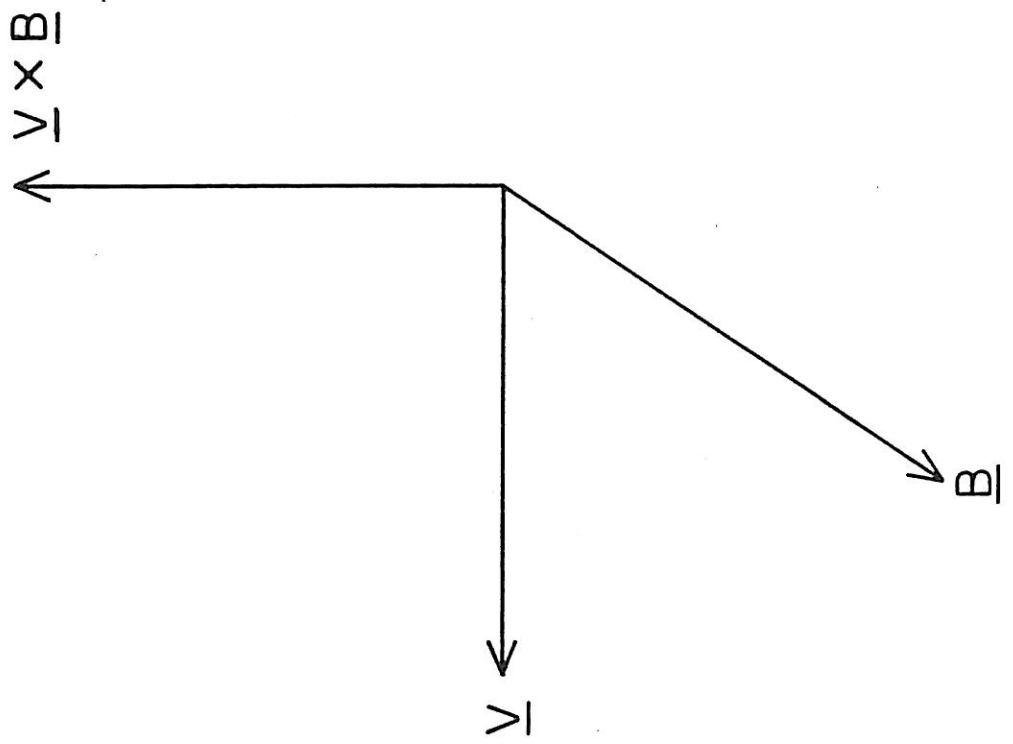


Figure 5. Coordinates for the spherical conductor are shown.



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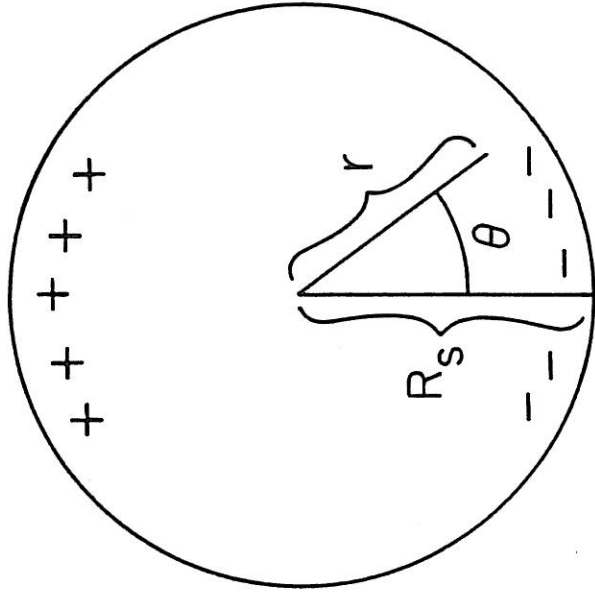


Figure 6. Plasma flow around a perfect conductor.

B - G85 - 587

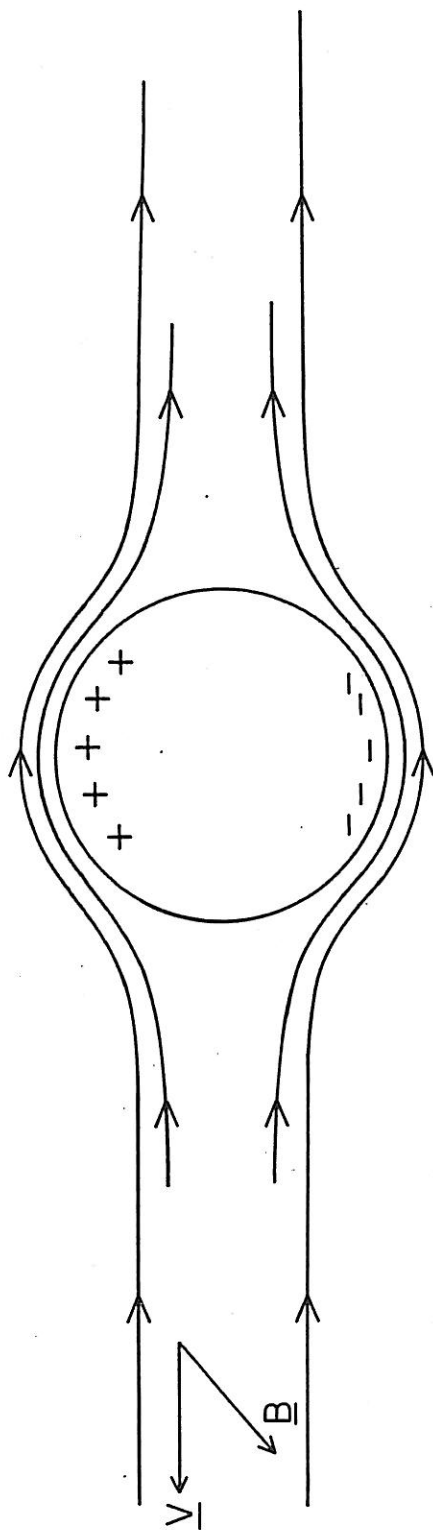


Figure 7. Plasma flow around a non-ideal conductor. Some plasma impinges on the conductor.

B - 685 - 588

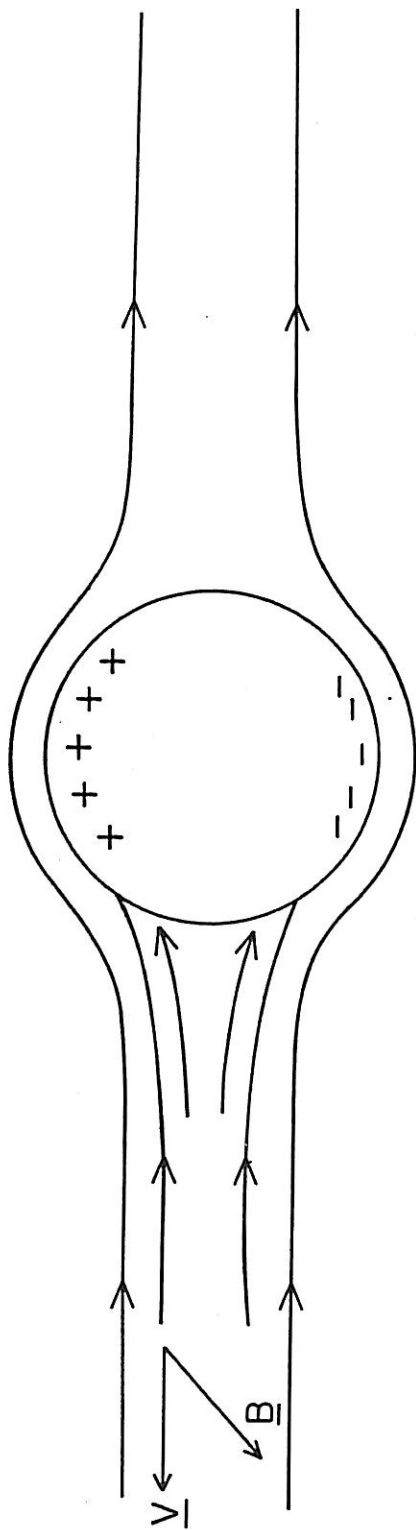


Figure 8. Plasma flow around the current wings.

B-G85-589

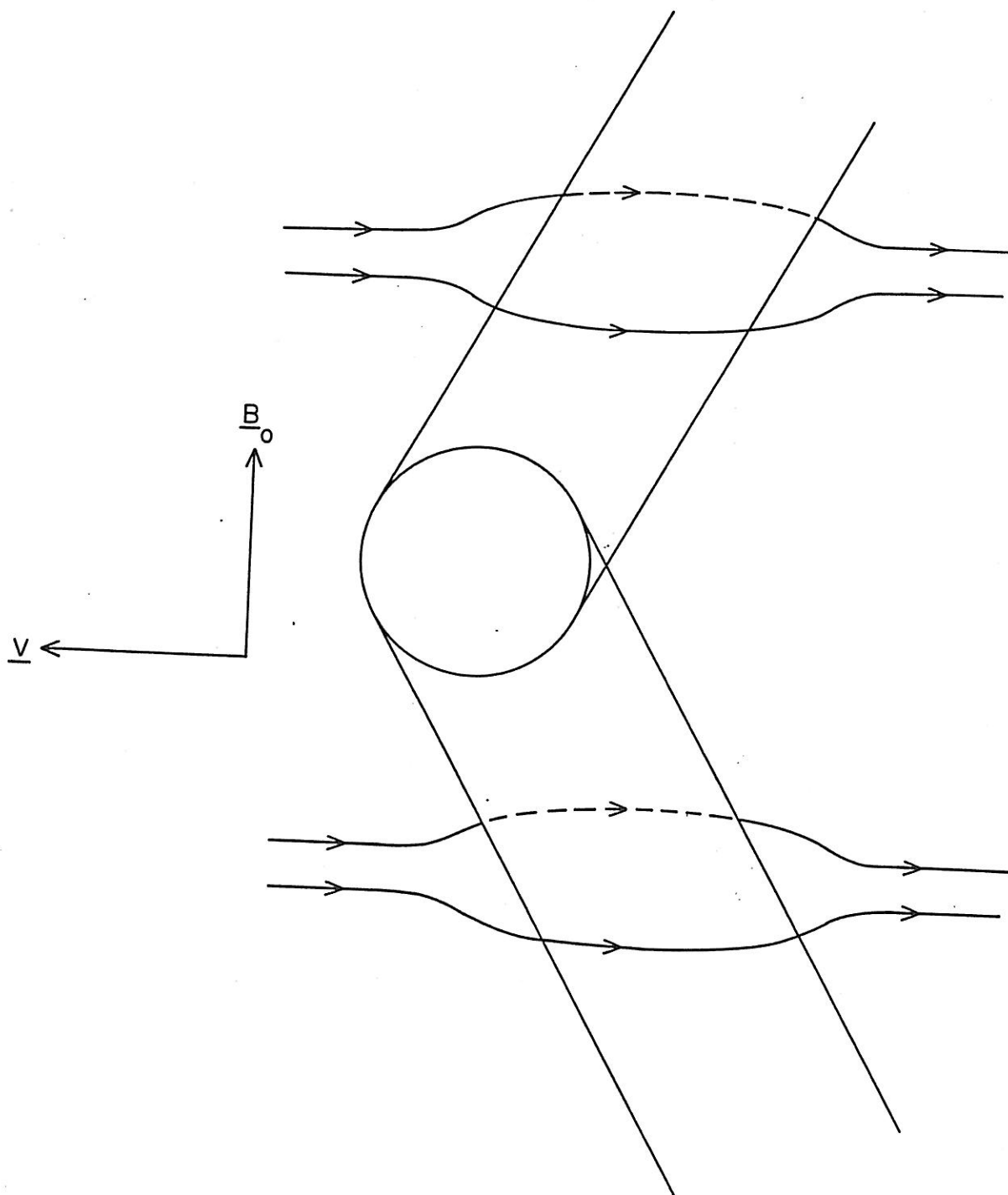


Figure 9. Coordinates for model of Neubauer.

B-685-590

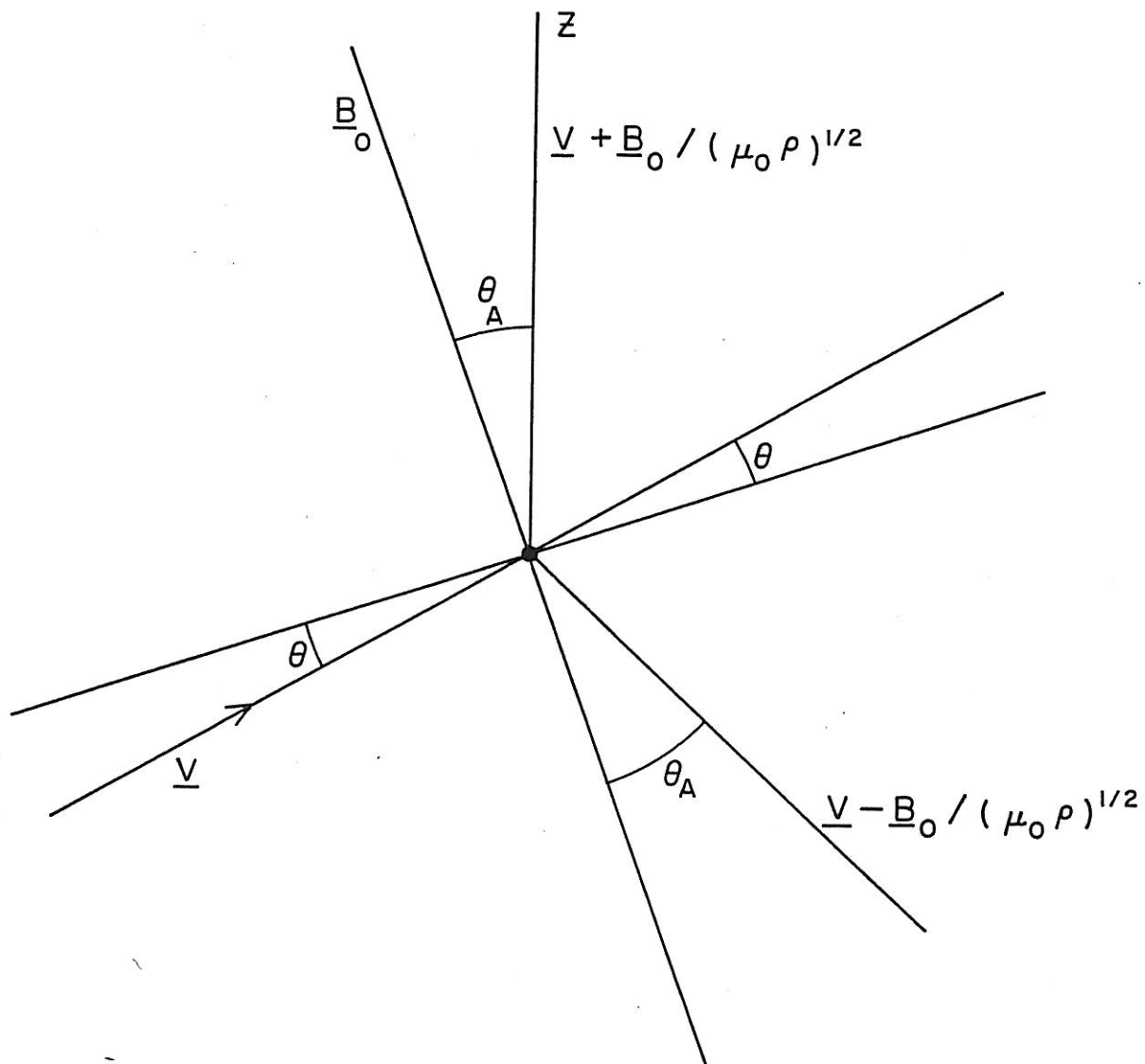


Figure 10. Trajectory for the space shuttle fly-around of the PDP.

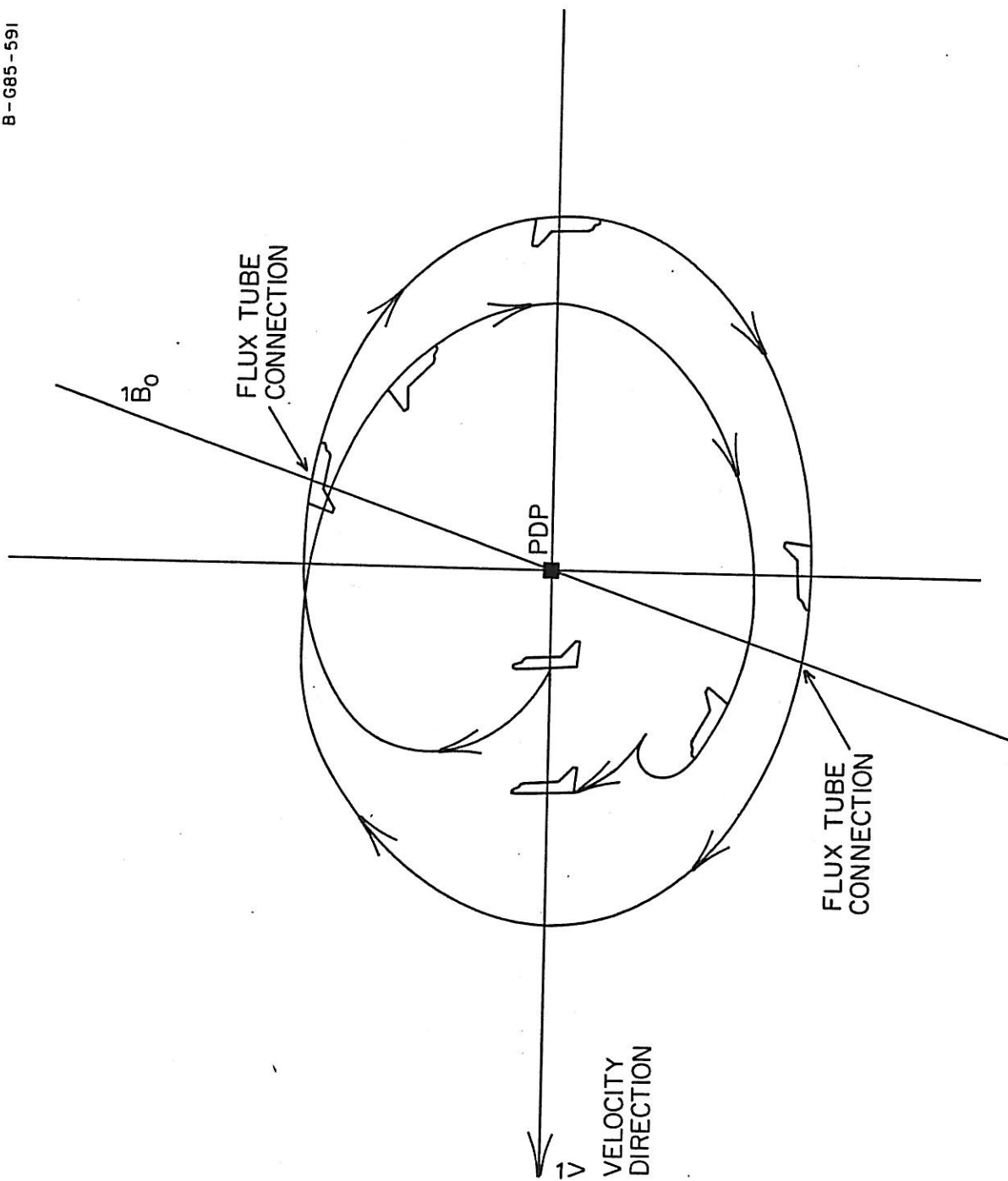
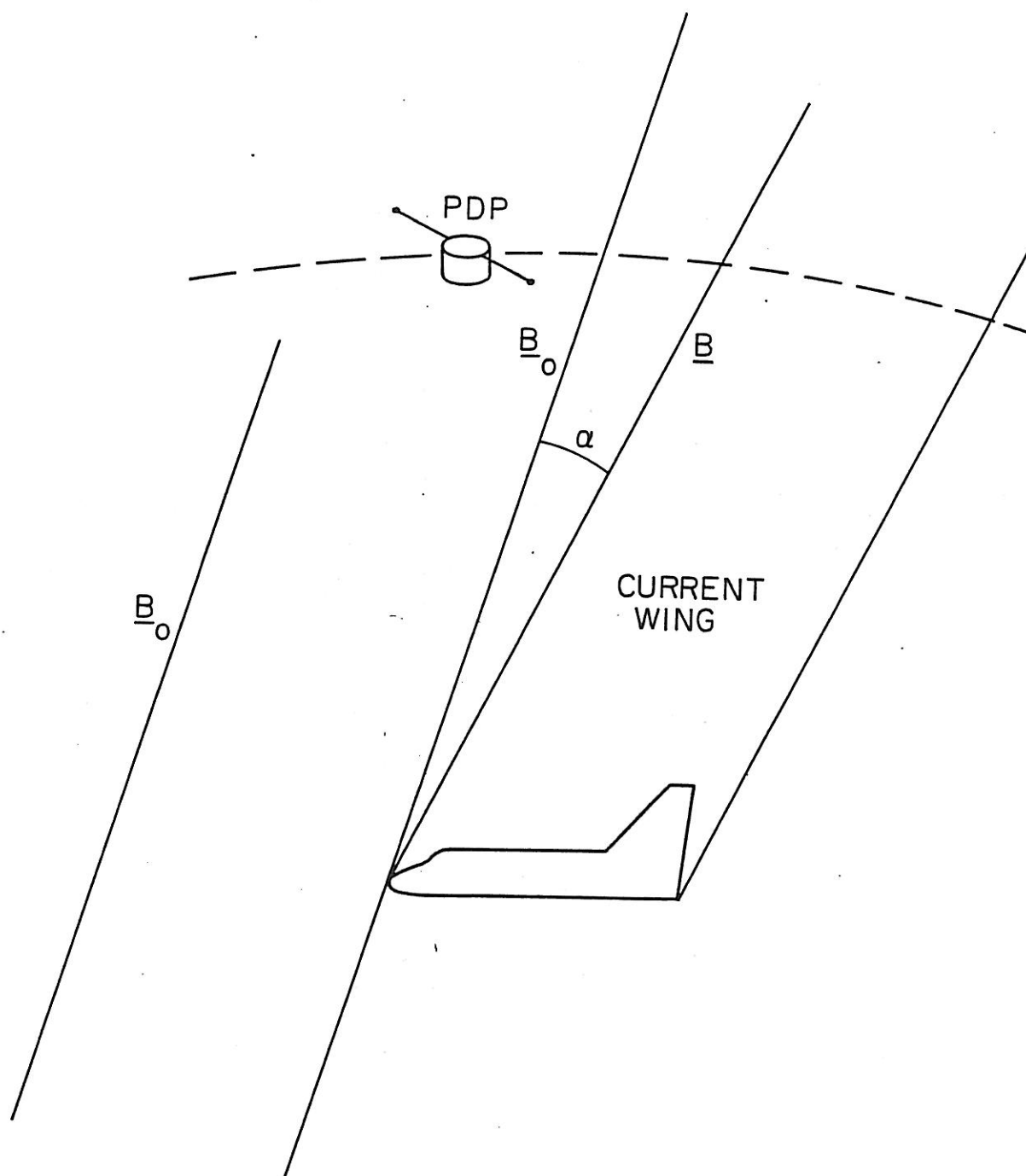


Figure 11. Current wing is at an angle relative to the undisturbed magnetic field direction.



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