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The double oval UV auroral distribution
2. The most poleward arc system and the dynamics of the magnetotail

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Abstract. The poleward arc system of a double oval distribution is shown to activate at the end of the optical expansion phase signifying the beginning of substorm recovery. The velocity dispersed ion signature (VDIS) can exist coincident with this discrete aurora developing on the most poleward oval. Although the VDIS is usually associated with ion beams in the plasma sheet boundary layer, it is demonstrated that the ionospheric signature is not beamlike but distributed in pitch angle. At the time when the double oval begins to form, the magnetic field in the magnetotail lobe becomes less flared and can show Pc 5 period oscillations. Similar pulsations also exist in the ionosphere associated with the most poleward oval and with stationary surge formation. Theoretical considerations link this phenomenon with a wave source tailward of $x_{GSE} = -30R_E$ and fast mode evanescent waves propagating earthward in the tail lobe region. In this case the magnetotail appears to act like a waveguide and the plasma sheet boundary layer as a resonance region. This implies that the coupling of this fast mode wave is with the plasma sheet boundary layer and not with dipolar like field lines. The implications of this for the reconnection model of substorms are discussed.

1. Introduction

During the later phases of a substorm, an auroral distribution known as the double oval forms [*Elphinstone and Hearn*, 1992; *Elphinstone et al.*, 1993]. In the companion paper to this [*Elphinstone et al.*, this issue; denoted DO1 in what follows], it was shown that two distinct source regions for discrete aurora exist, each associated with one portion of this "double oval." The more poleward arc system will be the focus of this paper. We shall present specific cases of the dynamics of the arc system illustrating an association between this development and the velocity dispersed ion signature (VDIS) which is linked to the plasma sheet boundary layer (PSBL). We shall also demonstrate a connection between this most poleward arc system and long period pulsations both on the ground and in the magnetotail lobe.

Pc 5 pulsations have frequently been explained by magnetic field line oscillations associated with Alfven resonances [e.g., *Kivelson and Southwood.*, 1985; *Chen and Hasegawa*, 1974]. Since the inner magnetosphere shows long period pulsation activity [e.g., *Takahashi et al.*, 1987] much work has been done exploring the governing mechanism in this region. For example, authors have investigated the cavity mode resonance as the cause for these pulsations on dipolarlike field lines [*Kivelson and Southwood*, 1985; *Allan et al.*, 1991; *Samson et al.*, 1992]. Some Pc 5 pulsations are clearly related to the inner magnetosphere such as those reported by *Elphinstone et al.*, [1995]. These, however, are probably related to Alfven-ballooning resonances [*Vetoulis and Chen*, 1994] or some other instability with high mode number rather than cavity modes.

While much work has been done on the inner magnetosphere there has also been interest in the outer regions. *Hansen and Harrold* [1994] investigated the possibility that resonant Alfven coupling with an incident MHD wave could occur on open field lines and in the PSBL. It was noted in this paper that the power absorption by the PSBL could represent a significant fraction of the energy produced in the magnetosphere during a substorm. *Siscoe* [1969] proposed that the differing wave speeds in the lobe and plasma sheet allow for resonances with periods in the 20 to 700 s range to occur in the tail. The concept that sections of the magnetosphere such as the flanks and the magnetotail might act as a waveguide can be found more recently by *Edwin et al.* [1986], *Walker et al.* [1992], *Wright* [1994] and *Rickard and Wright* [1994].

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Noise in the geomagnetic tail associated with plasma sheet expansions has been noted by *Russell* [1972] and long period pulsation activity has been found in both the flanks of the magnetosphere [*Zhu and Kivelson*, 1994] and the tail lobes [*Chen and Kivelson*, 1991]. Vortical flow in the magnetotail has been linked to Pc 5 pulsations on the ground by *Hones et al.* [1981]. Observations of this type tend to support the outer magnetosphere as the source for long period ionospheric pulsation activity.

In this paper we shall first establish that the arc system developing towards the end of substorm expansion can be linked directly with the plasma sheet boundary layer (PSBL) via the VDIS. We shall base this assumption of VDIS-PSBL correspondence on the previous work by *Bosqued et al.* [1993], the references therein, and *Zelenyi et al.* [1990]. Earthward streaming ions in the PSBL drift toward the central plasma sheet under the influence of a dawn to dusk electric field. The slower, lower-energy ions drift further before precipitating leading to the observed dispersion signature of ion energies decreasing with decreasing latitude. The exact form this dispersion signature takes is dependent on the magnetic field distribution, the electric field and the source region for the ions in the tail.

The second part of this paper shows the development of the most poleward arc system in conjunction with high-altitude and ground magnetic field data. Some theoretical arguments are used to distinguish between a near and distant tail source for the long-period pulsations which are seen. The final section of this paper looks at some of the implications of these observations with respect to the reconnection model of substorms.

2. The VDIS Particle Signature and the Double Oval Formation

This section presents the auroral dynamics of the most poleward arc system and compares this with particle and electric field data from the Viking spacecraft.

The Auroral Dynamics

Figure 1 shows the development of the double oval distribution on July 28, 1986. One can contrast the top left panel (only the main UV oval and the beginning of a substorm bulge are obvious) with the bottom right panel (a clear double oval is visible) to see the substorm related changes in the auroral distribution. Although there was some activity in the evening sector prior to 0535 UT a new activation began at this time. As seen in Figure 1, a substorm bulge has formed by about 0548 UT. The time period of interest for this study is after this when the substorm bulge forms into a double oval configuration. Between 0620 and 0628 UT a surge form is seen to develop toward the west as a traversing arc propagates toward the east. The arc system propagates into a region which was previously inactive (see bottom row at about 70 Mlat and 3 MLT CGM 1980). (For a second example, see Figure 10 in the work by *Elphinstone et al.* [1993]). By 0627 UT the most poleward arc system has developed a wavelike structure with a wavelength of the order of 1.5 hours MLT. This event is somewhat unique in that the Viking spacecraft is passing over the developing arc system almost exactly when it is brightening at the spacecraft location. The satellite positions at six specific times between 0617 and 0629 UT have been projected to an altitude of 120 km and are shown as white dots. The instantaneous position of the satellite is marked as a larger circle.

Convection and Particles

In the lower row of panels in Figure 1 the Viking spacecraft can be seen to be traversing the eastward developing arc system. The bottom left panel looks slightly different from the rest of the panels because the imager was operating in a different mode and so the field of view was more limited. The transformation to the polar coordinate system resulted in many blank regions for those locations where no data was acquired. The convective flow corresponding to Figure 1 is shown in Figure 2 and the time-energy spectrograms of particles in Plate 1. In this case a VDIS is seen coincident with the discrete auroral arcs developing along the double oval (0626-0627 UT in Figure 1 and Plate 1). Plate 1a shows the time interval between 0614 and 0630 UT, whereas Plate 1b focuses on the interval from 0624 to 0630 UT in order to illustrate the VDIS signature more clearly. The following main points can be made about the event shown in Figures 1 and 2 and Plate 1:

1. Low-energy electrons are seen poleward of the VDIS and the double oval distribution (points 1 and 2 in Figure 1 and between about 0617 and 0620 UT in Plate 1). These begin approximately at the location of the most poleward flow reversal (point 1 in Figure 1).

2. Between 0622 and 0624 UT the character of the electrons becomes more field-aligned and an intense upward electron beam is seen at about 0625:20 UT. These occur just equatorward of the second convection reversal at point 2 in Figure 2.

3. The main convection reversal occurs at about 0624 UT just poleward of the developing arc and the VDIS (point 3 in Figures 1 and 2). The ionospheric location of the infinite energy ion precipitation [see *Zelenyi et al.*, 1990] at 0624 UT is approximately consistent with this main reversal.

4. A VDIS signature is seen in association with the dynamics of the aurora at the beginning of substorm recovery indicating that the VDIS does not always occur in a steady state situation. Traces of trapped electrons are seen equatorward of this feature after about 0628 UT.

Although the VDIS is typically associated with earthward streaming ion beams in the PSBL it does not seem to appear as beamlike structures in the ionosphere. The case shown in Plate 1 is not an isolated case. A second example is given in Plate 2. This spectrogram was acquired on October 18, 1986, a few minutes after a double oval had developed after a substorm onset. In this case it is again clear that the ion pitch angle distribution is not beam-like and that the dispersion characteristics of the feature appears to be relatively independent of the pitch angle (only the upgoing loss cone is empty). For this example there is evidence of ion and electron conics at energies less than about 5 keV, but there is no evidence of energetic electron arcs. In agreement with this, the most poleward arc system of the developing double oval lies just equatorward of the VDIS.

3. ULF Pulsations in the Ionosphere and the Tail Lobes and Their Relation to the Double Oval Formation

The above examples provide evidence that the most poleward system close to midnight is associated with a tail process and is probably directly linked to processes occurring in or at the inner edge of the PSBL. We shall now illustrate how the double oval formation relates to more global magnetotail processes. Figures 3 and 4 demonstrate the relationship between high alti-

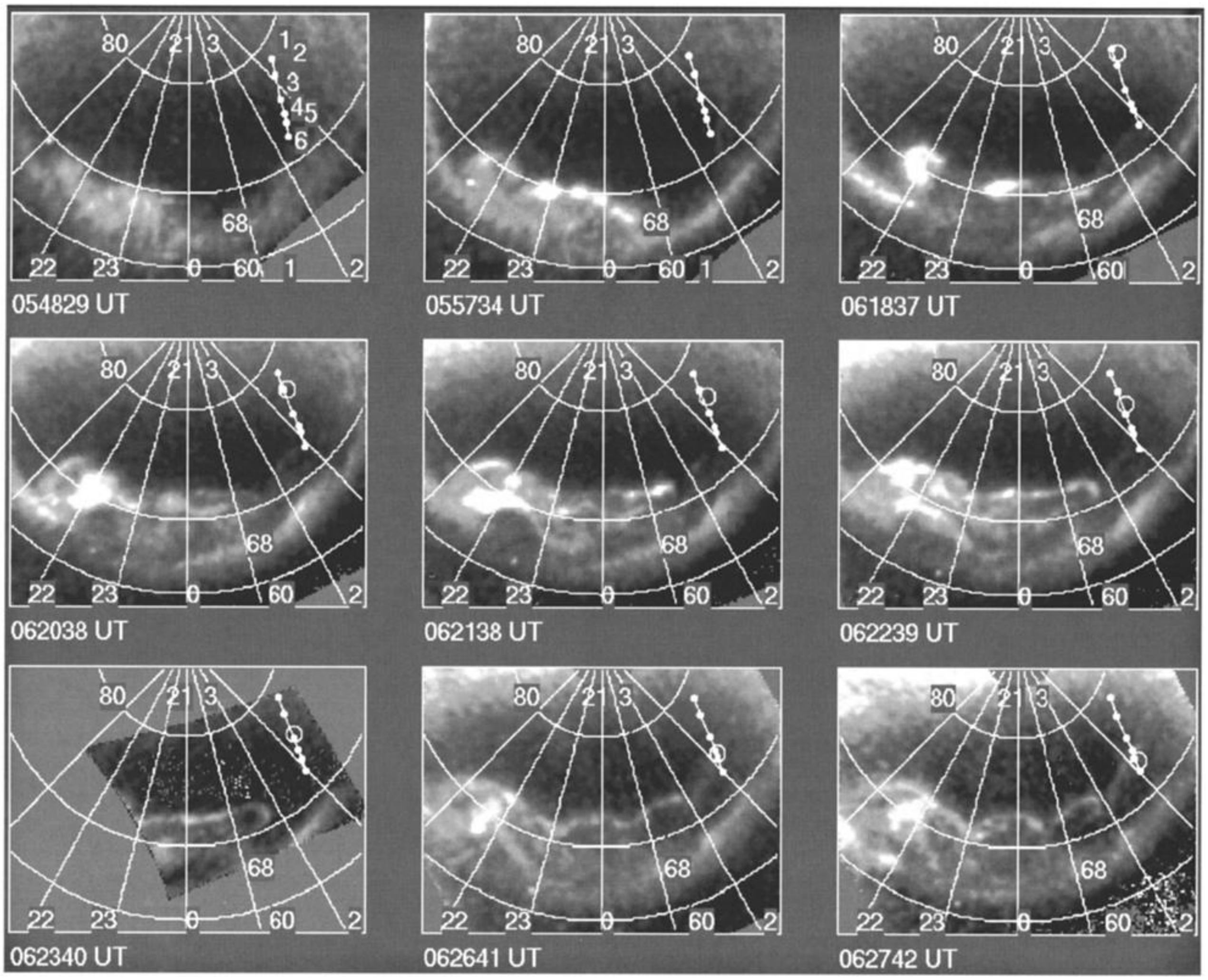

Figure 1. Viking auroral data showing the development of the double oval on July 28, 1986 at the same time as the VDIS is recorded by Viking. Points 1 to 6 (top left panel) correspond to 0617, 0620, 0624, 0626, 0627, and 0629 UT respectively along the Viking projected orbit. Note that the development of the most poleward oval occurs independently of a substorm bulge or of any more equatorward activity. The lower panels correspond to the time when the satellite encounters an auroral arc system and the VDIS simultaneously. The larger white circle shows the instantaneous location of the satellite projected to 120 km altitude. Local times (CGM1980) from 21 to 4 MLT are shown every hour and 60, 68, and 80 MLAT are also displayed. White corresponds to the most intense emissions.

tude observations in the lobe (by IMP 8) and the formation of the double oval for an event on July 29, 1986. Between 0728 and 0743 UT the substorm expansion bulge develops (top rows of Figure 3). Between 0753 and 0800 UT a traversing arc has intensified in the form of a vortex street. After this time there is a gradual formation of a large scale stationary surge form near 22 MLT (see *Cogger and Elphinstone* [1992] and Figure 1 in DO1). This forms in conjunction with brightenings, every 5 minutes or so, on the most poleward oval. Baker Lake is beneath this poleward arc system at about 75 MLAT near midnight (see bottom row of Figure 3). By 0822 UT the double oval is clearly established in the morning sector. This corresponds to the recovery of the H bay at Baker Lake. Observations at IMP 8, which was located in the northern tail lobe at GSE (-28.3, -9.6, 14) R_E, showed B_x GSM decreasing and B_z GSM becoming less negative beginning at about 0750 UT (see Figure 4). This implies that the tail lobe was becoming less flared between 0750 and 0820 UT. This occurs coincidently with the H bay intensification seen at Baker Lake and the development of the traversing arc system. The footprint of IMP 8 using the *Tsyganenko* [1987] model is marked by a large circle poleward of 80 MLAT in Figure 3. Magnetic observations at IMP 8 show periodic fluctuations in the transverse (B_z) and parallel (B_x) components at about 3.3 mHz (middle and bottom panels of Figure 4). The compressional component (B_x) appears to lead the transverse one by about 90 deg.

In the ionosphere pulsations beneath the developing most poleward arc system occur which bear a remarkable resemblance to the ones seen in the tail lobe (top panels of Figure 4). Pulsations in the H component at Baker Lake begin at about 3.8 mHz and then drift in frequency to about 2.8 mHz. The Y component (not shown) at Baker Lake sees a weaker signal at 3 and 3.8 mHz. These long period pulsations are not seen at stations located further equatorward. From this it appears that the

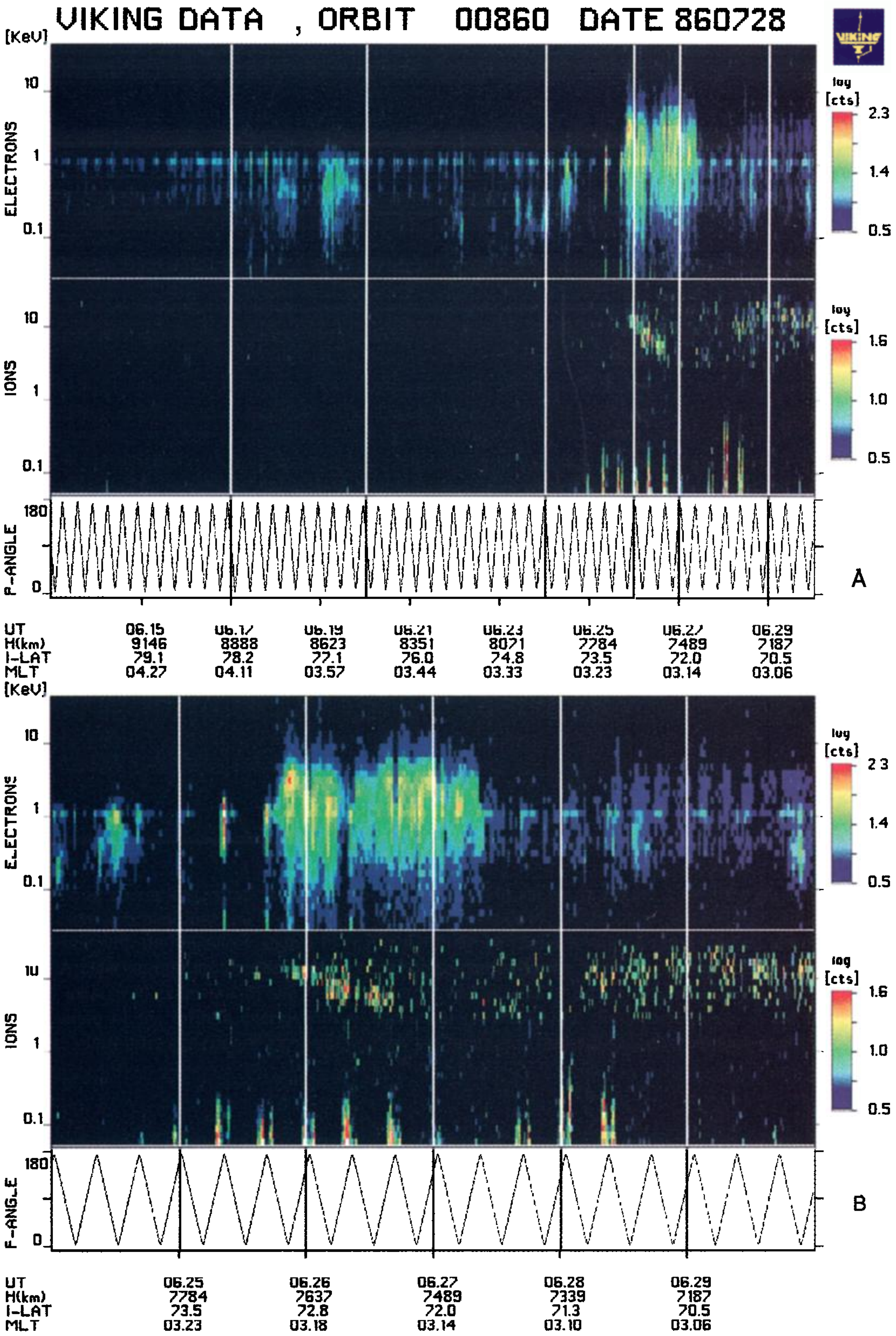

Plate 1. Viking energy-time particle spectrograms for the event shown in Figure 1 on July 28, 1986. Plate 1a shows the more complete interval with vertical lines drawn at 0617, 0620, 0624, 0626, 0627 and 0629 UT in correspondence with the trajectory shown in Figure 1. Plate 1b shows a more limited interval around the VDIS signature. A clear auroral arc can be seen to occur coincident with the VDIS signature. Low-energy electrons (top panel) exist well poleward of the VDIS signature and plasma sheetlike electrons begin about where the inferred position of the infinite energy ions would occur (≈ 0624 UT). Red corresponds to the most intense fluxes. The VDIS does not consist of beamlike ions but rather has fluxes distributed in pitch angle.

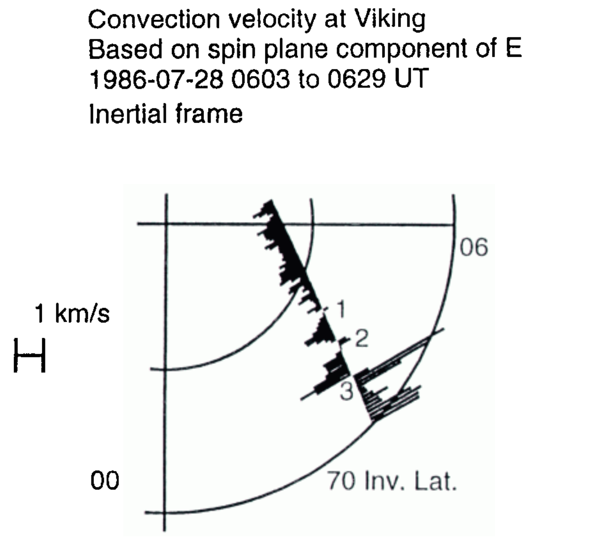

Figure 2. The convection velocity seen on the Viking satellite corresponding to the event shown in Figure 1 and Plate 1. The flow reversals seen at points 1 to 3 correspond to 0617, 0622, and 0624 UT respectively. All of these flow reversals occur poleward of the VDIS signature.

pulsation activity is linked to the development of the most poleward system. The similarity of frequencies seen both in the tail lobe and in the ionosphere associated with the formation of the double oval imply that the process affecting the tail lobe can be linked to the formation of the double oval configuration.

Polarization of a Fast Mode Wave in the Tail Lobes

In order to investigate in more detail the event described above it is informative to study the polarization characteristics of a fast mode wave propagating in a waveguide. The IMP 8 observations occurred in the tail lobe region where the Alfven speed is quite high compared to the plasma sheet region which has a relatively low Alfven speed. Characterizing the tail as a central region of low Alfven speed surrounded by regions of higher speed, we might expect it to act as a waveguide. Figure 3 illustrates a possible view of the magnetotail associated with this event. We shall further idealize this by considering the simple case of a field reversal at $z = 0$ with $|\mathbf{B}|$ constant on either side of $z = 0$. In the higher Alfven speed regions ($\omega^2/v^2(z) < k_x^2$) the wave has an evanescent structure in z. The WKB solution in this case can be written in the form:

$$\mathbf{b} = \left[b_{x0}\hat{\mathbf{x}} + b_{z0}\hat{\mathbf{z}}\right] e^{\alpha k_z z} \exp i\left[\beta k_x x - \omega t\right], \tag{1}$$

where k_x, $k_z(z)$, and ω are all real, and $\mathbf{b}$ represents the perturbation magnetic field. This formulation can explain the polari-

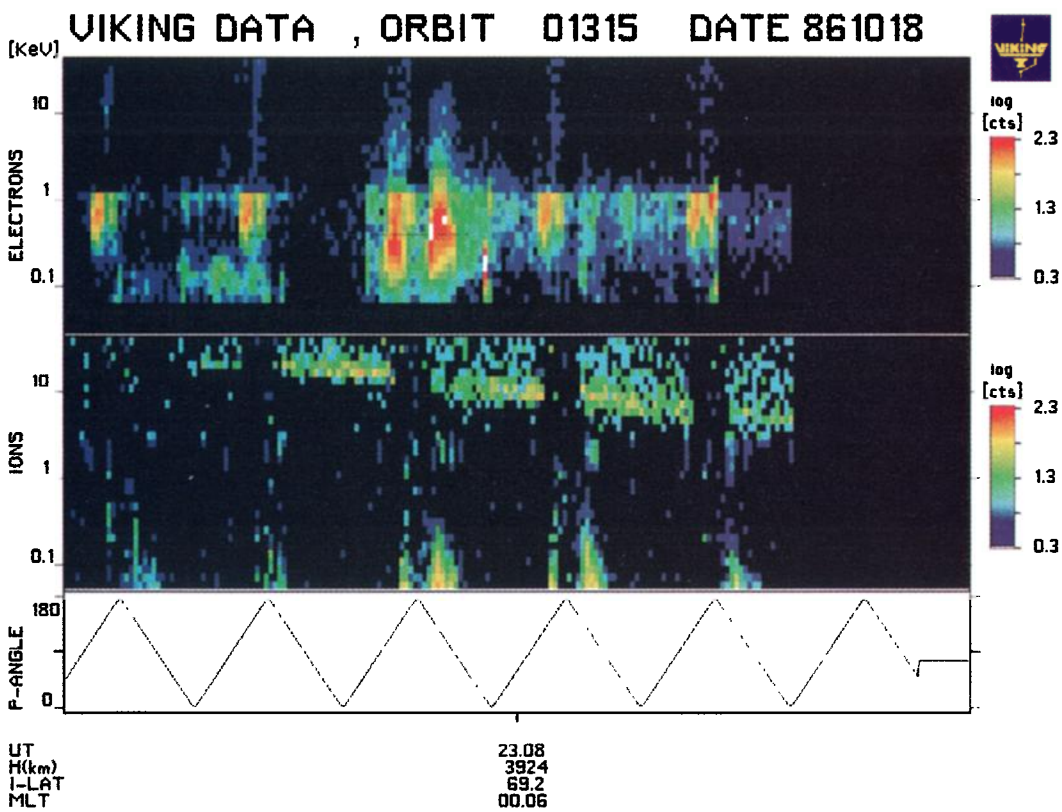

Plate 2. Viking energy-time particle spectrogram taken on October 18, 1986, covering from 2307 to 2309 UT. It was acquired about five minutes after the formation of the double oval configuration. In this case the VDIS lies poleward of the arc intensification but has a similar pitch angle distribution to that in Plate 1.

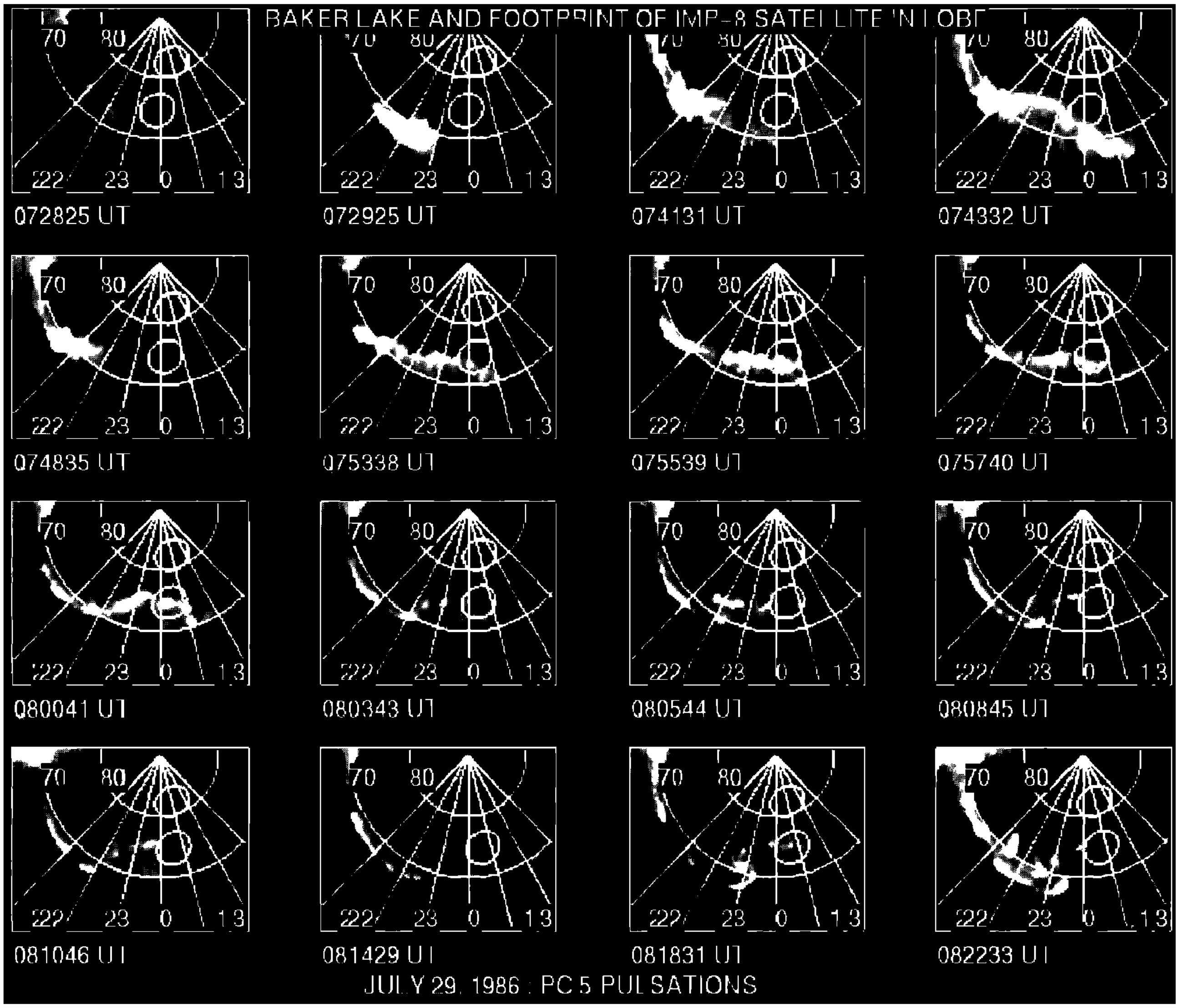

Figure 3. The evolution of the double oval distribution on July 29, 1986. This occurs coincident with the beginning of magnetic pulsations in the Pc 5 range on the ground and at IMP 8 located in the tail lobe (Figure 4). A stationary surge also develops at this time (see images in the lower row). The field of view at Baker Lake is shown by the circle near midnight and 73 deg while the projection of the IMP 8 satellite is shown by the circle closer to the magnetic pole. Magnetic latitudes of 70 and 80 MLAT, and MLT hours from 21 to 3 MLT are shown in CGM 1980 coordinates. White represents the most intense emissions.

zation observations in the tail lobe which occurred in conjunction with the double oval development. We require (on grounds of vanishing energy density as $z \to \pm\infty$) that

$$\alpha = -1 \quad z > 0 \qquad (2)$$
$$\alpha = +1 \quad z < 0 .$$

The sign of β determines whether the fast mode is propagating toward or away from the Earth:

$$\beta = -1 \text{ propagation } (x \to -\infty) \text{ away from the Earth;} \qquad (3)$$
$$\beta = +1 \text{ propagation } (x \to +\infty) \text{ toward the Earth.}$$

The polarization of waves in (1) for various values of α and β can be studied by applying the condition $\nabla \cdot \mathbf{b} = 0$. Neglecting the z dependence of k_z we find

$$b_{zo} = -i\,\frac{\beta}{\alpha} \cdot \frac{k_x}{k_z}\, b_{xo} \qquad (4)$$

Thus depending on the relative sign between α and β, b_z and b_x are out of phase by either $+\pi/2$ or $-\pi/2$. In the plasma sheet or the low Alfven speed region $(\omega^2/v^2(z) > k_x^2)$ the WKB solution for a waveguide has an oscillatory nature in z (in contrast with the evanescent lobe region), and has the property that the x and z components of the perturbation field are either in phase or 180° out of phase. This result can be derived in a manner similar to that given above. We conclude that the polarization

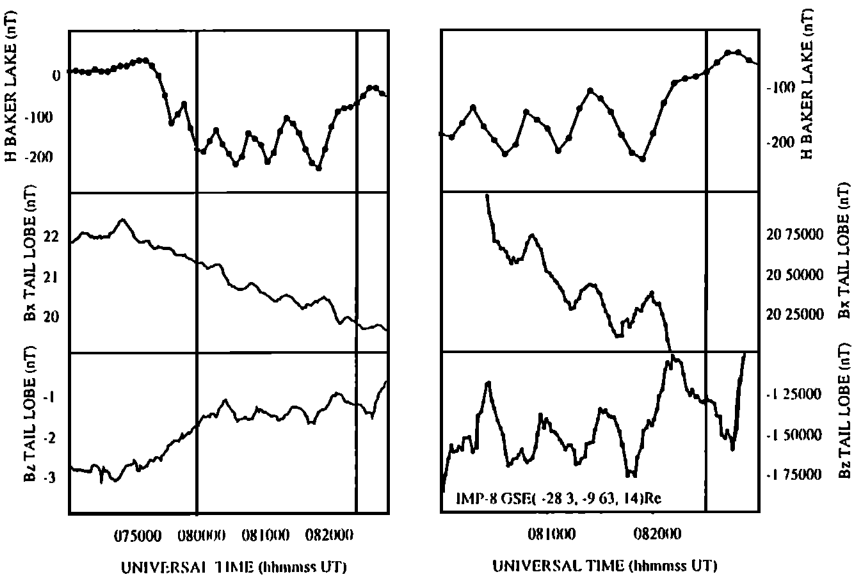

Figure 4. (top) Pulsations at about 3.3 mHz in the X magnetic field component at Baker Lake which is directly underneath the most poleward arc system. (bottom) Pulsations also near 3.3 mHz in the transverse (B_z GSM) and compressional (B_x GSM) components recorded by IMP 8 in the tail lobe at the time when the tail becomes less flared. The compressional component leads the transverse component by about 90 deg.

of the transverse and compressional components should vary relative to the wave source as shown in Figure 5. The observations given in Figure 4 took place in the northern tail lobe. Thus they are associated with the solution in (1) with $\alpha = -1$. Further, we know that b_x leads b_z (see Figure 4) and so, according to (4), β must be positive (i.e., there is a propagation toward the Earth). Since the satellite is at x_{GSE} = -28.3 R_E, we can conclude that the source of the waves must be deeper in the tail than this location. On the basis of the ionospheric observations we know that there is a coupling with the ionospheric currents and that this coupling is associated with the most poleward arc system of the double oval. It appears that the wave

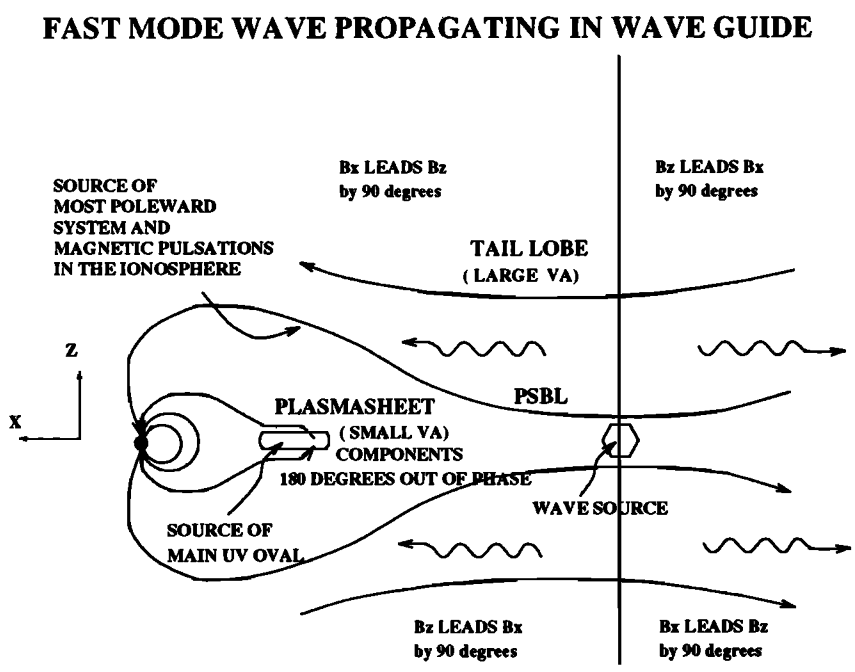

Figure 5. Schematic illustrating the phase relationship in the tail lobes expected at different locations relative to a wave source. The observations shown in Figure 2 support a source region for the waves tailward of IMP 8 at $x_{GSE} = -28.3$ R_E.

source that generates a fast mode wave propagating earthward can also be associated with Pc 5 wave pulsations in the auroral ionosphere linked probably with the PSBL.

4. Discussion

The examples presented above show that the development of the most poleward arc system can be linked via the VDIS to activity occurring in the outer portions of the plasma sheet and sometimes directly within the PSBL itself. This view of discrete arcs in the region corresponding to the low altitude projection of the PSBL differs from *Feldstein and Galperin* [1985]. It is more in accord with the view of *Burke et al.* [1994].

In the companion paper DO1, the most poleward arc system at different local times was associated with different magnetospheric regions. In the midnight sector it appears to be connected with the PSBL. In this paper we have seen that it is necessary to put the source of the lobe pulsations tailward of the IMP 8 satellite at $x_{GSE} = -28\ R_E$. Since the source of this wave is likely to also be the source of the ionospheric pulsations associated with the most poleward arc system, these arcs can be connected with this tailward source. We therefore require an energy source for this wave guide phenomenon to exist tailward of $x_{GSE} = -28\ R_E$ and to begin after substorm expansion phase onset. The following is one possible explanation for this energy source which is at least consistent with the observations.

Many observations have been interpreted as signatures of reconnection occurring in the nightside magnetotail [e.g., *Baker et al.*, 1984; *Baumjohann*, 1988; *Hones et al.*, 1979, 1984, 1987; *McPherron*, 1979; *Slavin et al.*, 1984, 1989, 1993; *Moldwin and Hughes*, 1993]. It is therefore worth considering this mechanism as an energy source for the above wave phenomenon. The following points in this paper are consistent with a reconnection process:

1. It was shown that the double oval development occurs when the tail lobe changes to a less flared condition beginning at about the time (0750 UT) when the high latitude arcs and the Baker Lake H-bay intensify. This change to a less flared condition is consistent with what one might expect if a plasmoid, which existed tailward of the IMP 8 spacecraft, retreated tailward. (See, for example, a schematic of the lobe field around a plasmoid in the work by *Slavin et al.* [1984]).

2. The waves seen in Figure 4 apparently originate from a source tailward of $x_{GSE} = -28\ R_E$. An obvious energy source for such waves would be the reconnection process and/or the release of a plasmoid downtail. The expansion of the plasma sheet in the mid-tail region which has been associated with the release of a plasmoid [*Hones et al.*, 1987] might be expected to generate normal modes of the magnetotail [*Siscoe*, 1969].

3. The double oval develops as a separate system from the expanding auroral bulge (see Figure 1). This development occurs as an eastward motion with little or no poleward motion. This could be interpreted as the result of a reconnection process which begins near midnight and spreads to greater Y values. The dayside regions of the most poleward arc system could be interpreted as the low latitude boundary layers becoming active as the plasma sheet refills.

4. The VDIS, which is also linked to the most poleward arc system, has previously been related to an X–line magnetic field geometry and to a reconnection process [*Kovrazhkin et al.*, 1987].

It is not clear that other boundary layer processes could be invoked to explain all of the above. The Kelvin-Helmholtz instability, for instance, is unlikely to generate the observed pulsation activity in the tail lobes. Although it is interesting that the reconnection substorm theory does so well in explaining the above observations, it should be noted that none of these observations can say anything for the role which reconnection might have concerning substorm onset. Thus the development of the most poleward arc system in the late stages of a substorm may be linked to reconnection processes in the magnetotail whereas the onset mechanism may instead by linked to near Earth processes. This supports the view put forth by *Kennel* [1992] in which these two regions can act independently. The continued existence of the double oval later in the recovery phase, which has been discussed in DO1, may even be due to other, different processes. In the future, it may be possible to put the observations given in this paper into a substorm scenario similar to that suggested by *Lui* [1991].

We have also seen reasonable evidence linking ionospheric Pc 5 pulsation activity to the most poleward auroral oval, to the development of a stationary surge form (SSF), and to high-altitude lobe Pc 5 pulsations. While again there may be other explanations for coincidental pulsation activity found at these two widely separated locations, a scenario which is at least consistent is that a coupling exists between an eigenmode of the tail and shear Alfven waves which link it to the ionosphere. On the basis of what is known about this most poleward arc system from the above observations, it appears that the coupling, in this case, occurs not in the near-Earth region but instead in the plasma sheet boundary layer and on open field lines in the tail lobes. Since this resonant absorption can conceivably be a significant portion of the substorm energy budget [*Hansen and Harrold*, 1994], this phenomenon should be seriously investigated in the future. While coupling may still occur in the more dipolar regions of the magnetosphere the observations presented here demonstrate that this need not always be the case. Further, as shown by *Elphinstone and Hearn* [1993], the motion of the accompanying auroral arcs (and thus the phase relationships in the magnetic pulsation signatures) may depend on the source motion. Multiple arcs moving poleward may imply a tailward moving source, while equatorward drifting arcs imply an earthward moving source. Therefore using field line resonances and the associated phase relationships as evidence for near Earth substorm onsets [e.g., *Samson et al.*, 1992] must be viewed with caution.

Summary

The outermost oval of the double oval configuration can occur colocated with the VDIS which indicates that the associated discrete aurora is related to a plasma sheet boundary layer phenomenon. This poleward oval can develop in conjunction with the tail lobe field becoming less flared. Coincident with this lobe change, Pc 5 period fluctuations begin both at the ground and in the lobe. This suggests a fast mode wave propagating earthward in response to a disturbance leaving the magnetotail. The source region for the waves was found to be tailward of $x_{GSE} = -28\ R_E$. A possible energy source for these waves which is at least consistent with the observations is a reconnection process occurring tailward of this point.

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