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CLUES TO PLASMA PROCESSES BASED ON FREJA UV OBSERVATIONS

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ABSTRACT

The Ultraviolet Imager on board the Freja satellite was designed to provide real-time monitoring of the instantaneous auroral distribution from space. Auroral features are accompanied by sheets of current which commonly have perturbations which grow and decay producing obvious distortions in the aurora which are often periodic in local time. Typically the character of these features are consistent with a shear flow type instability. The periodic features were found to occur throughout the afternoon/midnight and as well they appeared at a variety of locations within the auroral distribution implying a very flexible physical process for their generation.

INTRODUCTION

The phenomena collectively known as the auroral distribution is a by product of the dynamic interaction which takes place between the highly ionized plasma of the magnetosphere and the partially ionized ionosphere. Because of the nature of the ionosphere/neutral atmosphere interface this distribution is constrained to a vertical region which is much smaller than its two-dimensional horizontal extent. That extent (crudely a concentric band of emissions roughly centered on the magnetic dipole axis intersection with the Earth's surface) in latitude and longitude (or local time) reflects the operation of plasma processes which result in a significant precipitation of particles into the ionosphere. The fields (primarily magnetic) which couple the magnetosphere to the ionosphere and thus accommodates this precipitation of particles provides the means whereby the vast volume of the magnetosphere can be interrogated by observing the emissions from the ionosphere. Satellite imaging systems have utilized this phenomena to make a number of important advances in the understanding of the large scale character of the magnetosphere /1,2,3/. Because of technical limitations early usage of such large-scale measurements focussed primarily on the morphology. That is the pattern of aurora indicated where significant particle precipitation was occurring (e.g. /4/) which in turn could be associated with various source regions in the magnetosphere. This continues to be a major contribution as improvements in other techniques (e.g. field line tracing) and measurements (e.g. particle/field characteristics) enables more information to be extracted from the image data.

As technical advances have been made the ability to address the actual physical processes has become possible. The first such major advance came with the ability of the DE 1 imager to record long sequences of image data over a variety of wavelength bands to provide some indication of particle characteristics and ionospheric conditions /5,6/. Of particular significance was the utilization of ultraviolet wavelengths which allowed the imaging of the auroral distribution even under full sunlight. The UV imagers on the Viking satellite adopted this approach and further allowed for the acquisition of image data with true two-dimensional characteristics /7/ by eliminating any difference in acquisition time within the image. This coupled with the relatively short image repeat time (generally 1 minute between images though often less) allowed for dynamic studies of the explosive auroral processes to be undertaken /8,9/. Spatial resolution and image repeat time were however, sufficient only to illustrate the coherent dynamics which seem to often occur throughout the auroral distribution.

The Freja UV imagers were designed to remove these constraints so that the optical data could provide better information about the plasma processes inherent in the precipitating particles causing the aurora. In particular certain morphologies of periodic features within the auroral distribution suggest interesting wave activity operates under a variety of conditions. The purpose of this report is to illustrate the kinds of this coherent emission which commonly occur, discuss certain characteristics and relate them to suggested plasma processes and their magnetospheric source location.

DATA SELECTION

Useful data from the Freja UV imager was acquired during the fall of 1992. Approximately 560 passes over ground stations were inspected to investigate the character of periodic phenomena in the auroral distribution. The Freja UV imager /10/ contains 2 cameras which acquire images simultaneously. One of the cameras operates at Lyman-Birge-Hopfield (LBH) wavelengths (134-180 nm) while the other extends from 125 to 150 nm thereby covering the important 130.4 and 135.6 nm atomic oxygen lines as well as most of the LBH bands. The instrument design and satellite orbital characteristics provide spatial resolution at nadir of approximately 10-15 km and temporal resolution of .35 seconds with images acquired as fast as every 6 seconds. Because of the image sizes chosen and telemetry rate restrictions the image repeat time is not constant. Generally an image from each camera is obtained in sets of 3 with 6 seconds between pairs (ie covering 12 seconds total). It then takes approximately 140 seconds for image memory to be cleared before the next set of 3 images can be obtained. In this manner typically 20 image pairs are obtained per ground station pass. During this period of time, because the Freja satellite only has an apogee of 1700 km, the viewing conditions change considerably. This causes each set of 3 images to view a different portion of the auroral distribution. As with some earlier imaging systems it may take 15 minutes to get measurements of a reasonable fraction of the auroral distribution although each portion has high temporal resolution data available.

OVERVIEW OF PERIODIC PHENOMENA

Casual inspection of the morphology of the auroral distribution reveals a complicated set of optical forms whose significance is often difficult to ascertain. While as noted above certain morphologies are of themselves very important, the difficulty in addressing questions of plasma processes is that the scale of the phenomena is often such that *in situ* measurements are often difficult to obtain. Although certain plasma/field characteristics are crucial to establish what specific plasma process is operating, optical measurements can provide a number of clues about the source mechanism which results in these forms and where within the magnetosphere/ionosphere regime the process takes place. Pioneering work done using ground-based data by Davis and Hallinan /11/ showed that the character of discrete arcs displaying periodic distortions could provide useful information on the plasma processes operating above the auroral ionosphere. Distortions which have a periodic (in longitude) nature are particularly suited to providing information about potential plasma processes. Such features have been discussed previously /12/ and often are a transient phenomena. Murphree et al. /13/ and Murphree et al. /14/ have shown that series of distortions like this can occur at all MLT implying quite general conditions for their existence. Schematically Figure 1 shows the more common ionospheric locations for these features. Distortions in discrete arcs are most commonly seen in the afternoon to midnight sector. But as well they appear at high latitudes in the morning sector. The well known omega bands /15/ are common during substorm periods at lower latitudes in the morning sector and a new observation (in the UV) is that of the previously observed undulations in the diffuse aurora in the evening sector.

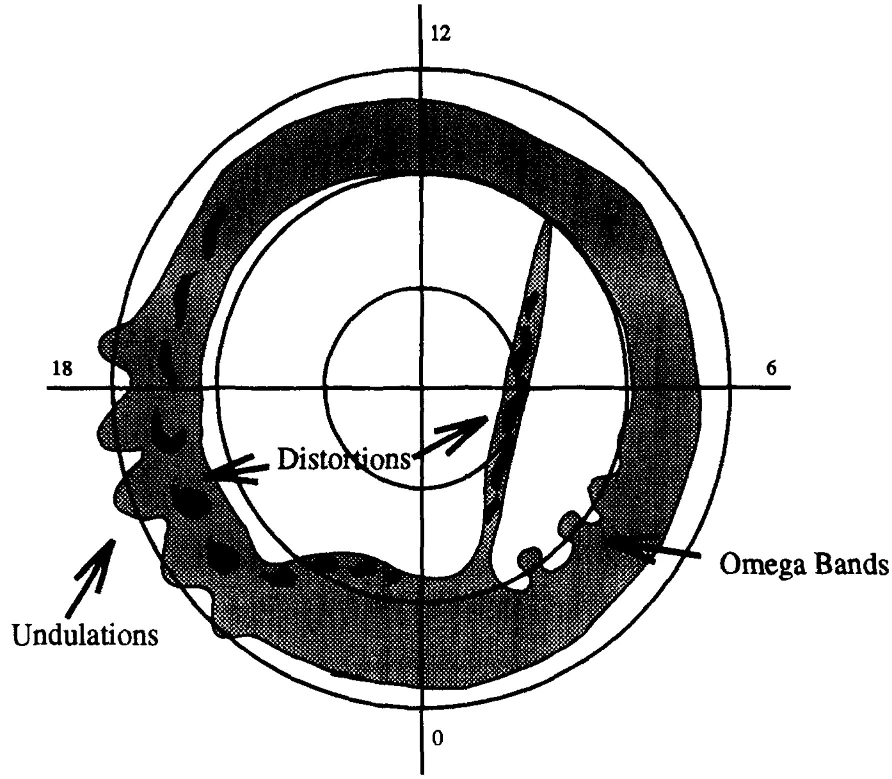

Fig. 1. Schematic illustrating regions of the auroral distribution where periodic distortions are commonly observed.

DISTORTIONS IN DISCRETE ARCS

Discrete auroral arcs are the result of accelerated portions of the precipitating particle distributions. Although dependent to an extent on the method used to observe them, such arcs essentially consist of intense regions of emission whose latitudinal extent is much smaller than their longitudinal one. Typically covering several 10's of kms in latitude they are associated with regions of strong electron precipitation and hence upward field-aligned current /16/. Although often thought of in terms of a 'quiet' configuration wherein a uniform sheet of current is identified with a longitudinally uniform region of emission, this in reality is generally not the case. Discrete arcs typically are distorted both in terms of their spatial morphology and intensity. Deviations from uniformity can be extreme (as for example in the case of substorm surges) or else constrained to minor perturbations on the background system presumably depending on the driving process. Such distortions have been studied using ground based optical instrumentation /17,18/ and using satellite based imaging techniques /13,14/. Although any such distortion can reasonably be viewed as the result of some plasma process, the observation of periodic distortions suggests the existence of a coherent plasma instability operating over (in some cases) rather extensive regions. Several examples of such periodic distortions are shown in Figure 2. The images are displayed with color representing intensity - with red the most intense emissions (all data are from the LBH camera). The data in the top left image (acquired 2 November 1992 at 0959:44 UT) are from the midnight sector and show periodic (in MLT) distortions which occur pre-midnight as intense bright features. In this particular example the periodic features occur within the main part of the auroral distribution and seem to extend from the poleward region near midnight to the equatorward region near 20 MLT. A common feature of distortions on this scale is the counterclockwise sense of deformation as seen from above the northern hemisphere auroral distribution (ie looking parallel to the local magnetic field direction). The temporal development of these features is such that the deformation rotates counterclockwise which when viewed from the ground, corresponds to a clockwise rotation. This deformation observed is consistent with previous Viking measurements (e.g. /13/) although for such periodic features the rotational sense was rarely

Fig. 2. Examples of periodic distortions in discrete arcs.

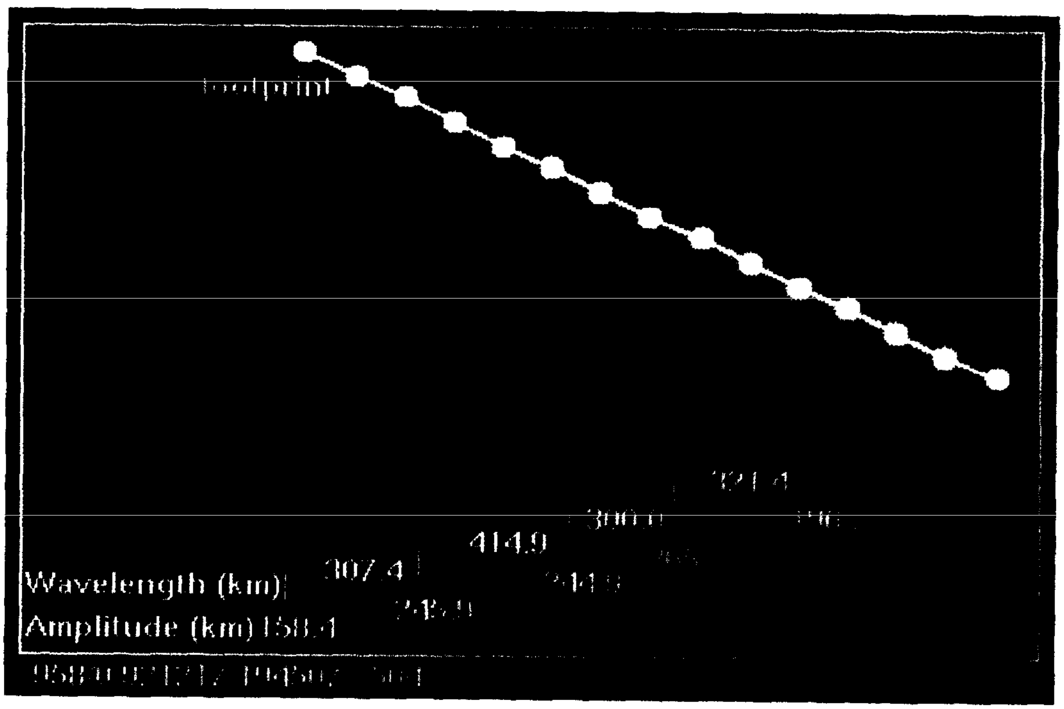

Fig. 5. Example of undulations in the equatorward auroral boundary.

identifiable. The top right image of Figure 2 (acquired 10 November 1992 at 0845:22 UT) shows a further example of forms in the premidnight sector. Once again the forms seem to be rotated in a counterclockwise sense and all seem to be rotated by the same amount. The bottom left image of Figure 2 (15 November 1992 at 0310:44 UT) shows more extended series of distortions in the midnight sector. In this example (although difficult to see in this presentation) the distortions form the bulk of the auroral distribution. That is the distribution is relatively narrow at this time and the distortions therefore occur throughout its latitudinal extent. As is clear in the image the intensity of the distortions increases towards midnight and in fact they merge into a substorm surge. Such distortions have recently been discussed in the context of substorm onset precursors /19/ and proposed to be the result of an interchange instability acting in the substorm onset region in the magnetotail. Finally, the bottom right image of Figure 2 (12 December 1992 at 2055:08 UT) shows a series of distortions which occur on the poleward boundary of a substorm bulge.

The location of the periodic features within the auroral distribution is significant from the perspective of where their creating plasma processes operate. There appears to be no specific dependence on MLT or magnetic latitude. This is apparent when individual cases of periodic features are analyzed. Because of orbital constraints the passes sampled were confined to afternoon/early morning MLT sector. Figure 3 shows the probability of occurrence for distortions in general as a function of MLT.

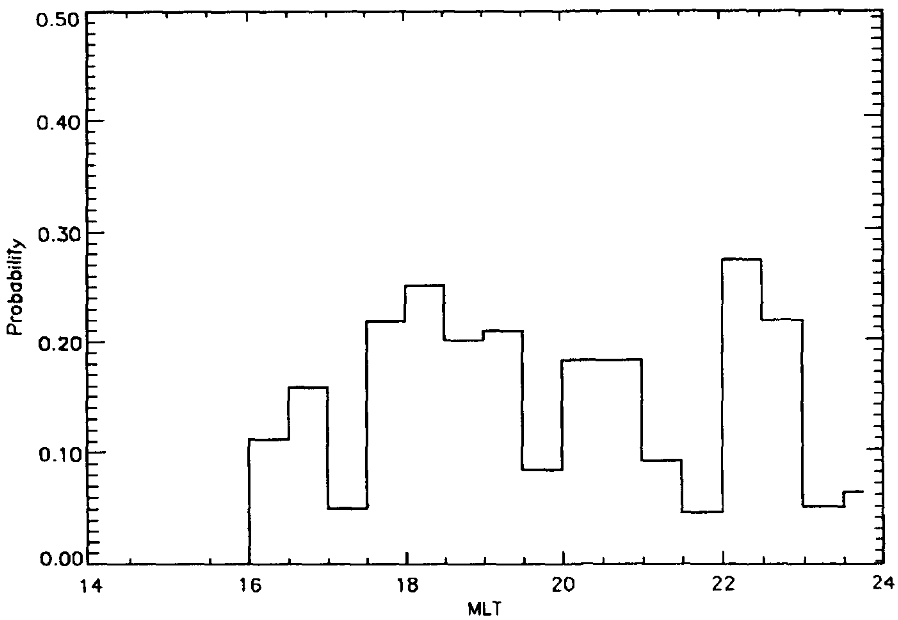

Fig. 3. Probability of observing distortions.

The cutoff prior to 16 MLT is due to lack of sampling. Although variable there is a 20% probability of observing distortions throughout much of the evening/premidnight sector. This is consistent with the earlier conclusions of Murphree et al. /13/ based on Viking images. As well the mean MLT for these observations was 21.3 MLT and the median 21 MLT indicating a rather uniform distribution.

The dataset containing periodic distortions has been analyzed to determine whether there are any consistent characteristics of this optical morphology. Preliminary work reported in Murphree et al. /14/ showed that the most obvious characteristic was a relationship between wavelength (ie distance between the distortions) and an estimate of the arc width. They reported that :

$$D = .22\lambda \quad (1)$$

where D is the extent (in km) of the arc system in the latitudinal direction and λ the wavelength. This form of relationship is (as will be discussed below) consistent with shear flow effects and therefore distortions such as these have generally been associated with plasma instabilities. Indeed similar spatial patterns to that of optical distortions have been reported in other physical quantities. Clauer et al. /20/ have described trains of vortices utilizing magnetometer data and constructed F-region convection flow plots illustrating the rotation character of the disturbances. Burke et al. /21/ have used *in situ* satellite measurements to infer plasma flow patterns during two substorm periods. Recently Potemra et al. /22/ have related satellite optical and *in situ* data to attempt to establish the physical process by which at least one particular case of periodic arc system distortion occurs.

As noted above the existence of periodic distortions is relatively widespread in MLT and interestingly a clear peak in occurrence frequency at wavelengths of 152 and 290 km has been found /14/. The observation that periodic distortions can be associated with a number of spatial (and potentially topological) regions within the auroral distribution points to a plasma process which is capable of operating over widely separated regions. Although it is likely that such periodic features have slightly different characteristics in different topological regimes, the consistency of the wavelength distribution suggests that some basic physical condition(s) are generally satisfied just as for example the existence of field-aligned currents is unconstrained. A popular plasma characteristic invoked for understanding a number of ionospheric observations of vortical structures is the existence of shear regions within the plasma (e.g. /23/). These have been applied in a number of different topological regimes from presumed dayside magnetopause/boundary layer signatures /24/ to low-latitude nightside features such as omega bands /25/. The presence of a shear provides a source of energy (ie the spatial inhomogeneity of mass motion) from which instabilities can grow and modify the spatial distribution of plasma.

The relation obtained above between wavelength and arc width is theoretically expressed in terms of:

$$kL = .7 \tag{2}$$

(e.g. /26,27/) where k is the wave number, L is the width of the shear layer and the constant is consistent with the relationship noted above. As Murphree et al. /14/ proposed the arc width is a reasonable, but probably an underestimate, of the extent of the shear zone. A number of MHD simulations (e.g. /24/) have been performed to attempt to replicate these distortions and the above relationship is consistent with that required for maximum growth in the linear regime /26/. Most commonly this theory has been applied to periodic distortions observed in the afternoon sector. Shear flow in the equatorial plane results in flow dynamics governed by the vorticity equation :

$$\frac{\partial \Omega}{\partial t} = -\vec{v}\cdot\nabla_e\Omega + \frac{B_0 J_e}{H\rho} + \nu\nabla_e^2\Omega \tag{3}$$

where Ω is the vorticity, the subscript e denotes the equatorial plane, J is the field-aligned current, H the half thickness of the field-aligned currents around the equatorial plane and the last term represents viscous effects. Development of the field-aligned current (which ultimately results in precipitation of particles and hence optical emission) arises from the divergence of perpendicular current in the equatorial plane. Vo /28/ has used this model to successfully demonstrate the spatial morphology of the field-aligned current pattern under uniform and local driven conditions at the shear layer is consistent with the optical pattern. That is local perturbations in upward field-aligned current develop analogous to that of optical distortions.

Casual inspection of the dataset of these periodic distortions seems to indicate a variation in intensity of the distortions with MLT. This would imply a variation in the field-aligned current density of the perturbations along the shear layer. To see if this is a consistent effect the cases of periodic distortions were analyzed for their relative intensity along a given set of distortions. Figure 4 illustrates the results as a function of MLT.

In each example the distortion at the earliest MLT is used to normalize the series. Thus for example, orbit 370 indicates that as one proceeds away from midnight the intensity increases. Though there is considerable variation, it is clear that in the midnight sector the trend is for the distortions at earlier local times to be less intense than those at later times along the same feature. Typically then one expects the field-aligned current density to be greater near midnight, which is consistent with the locally driven case for the production of field-aligned current from the shear layer. This is not surprising if a process such as injection of plasma (e.g. during a substorm) results in a local shear flow enhancement. Such processes are thought to be more common in the midnight sector.

A final piece of information relevant to simulation of these features is the extent of the upward and downward field-aligned current regions in the ionosphere. Optically these would correspond to the peaks and minimums in intensity along the series of distortions. Contrary to Vo /28/ who showed that the upward field-aligned current was dominant spatially, optically the extent of the minimum is greater by a factor of 3 on average although this is highly variable. This maybe the result of plasma processes operating on the field-aligned current perturbations along the field line.

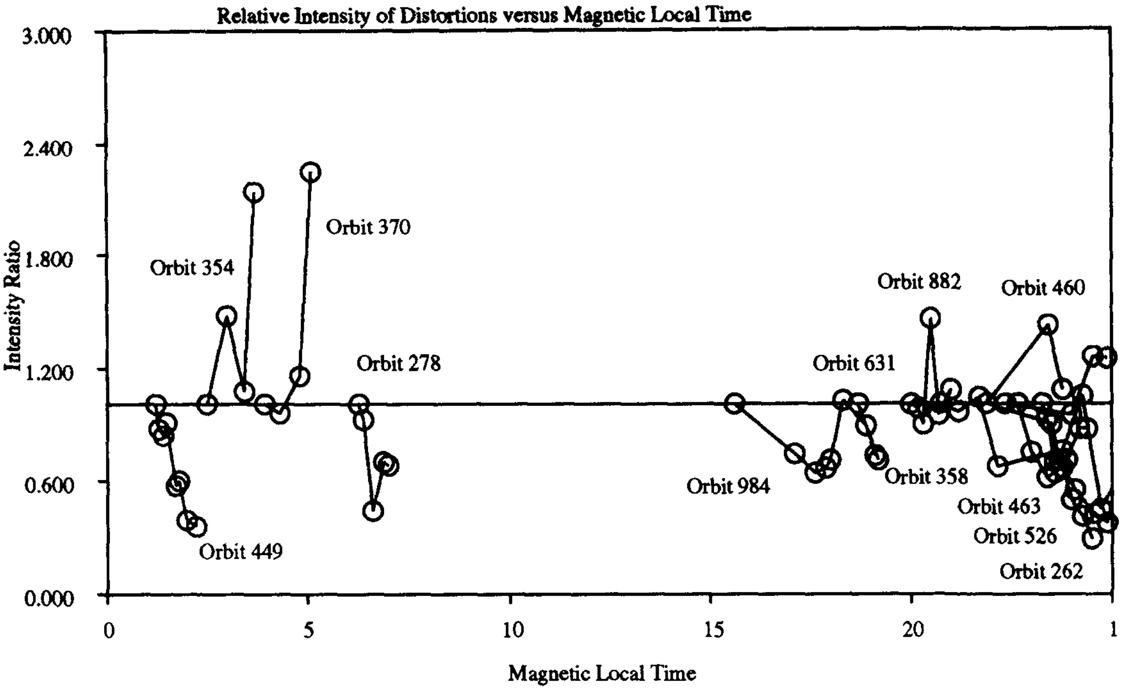

Fig. 4. Plot of the relative intensity of distortions along each series of periodic distortions. The relative intensity is normalized to the distortion at the earliest MLT.

UNDULATIONS IN DIFFUSE AURORA

Another type of periodic structure has been observed in the evening sector diffuse aurora. These forms, first reported by Lui et. al. /29/, have been termed 'undulations' and are identified by large-amplitude waveforms on the equatorward boundary of the diffuse aurora. An example of these periodic forms observed by the Freja UV Imager on 921217 is shown in Figure 5. The auroral distribution is characterized by several discrete arc systems in the poleward regions beginning about 19 MLT then extending toward midnight and a relatively uniform (in intensity) diffuse aurora forming the bulk of the emissions. The equatorward boundary of the diffuse emissions clearly shows a series of indentations over a region extending from 17 to 20 MLT. Interestingly the wave characteristics of these undulations are about twice that noted above for discrete distortions : the average wavelength of the forms is 336 km. In addition it is straightforward to determine the average distance between the crest (ie lowest latitude) and trough (highest latitude) to be 210 km. Both of these are consistent with the observations of Lui et al., /29/. Yamamoto et al. /30/ have categorized these features in terms of the amplitude to wavelength ratio : ratios less than 1 (Type I) have undulations which seem to be most commonly observed while ratios on the order of 1 or greater (Type II) are termed 'giant' undulations. The wavelengths and amplitudes tend to vary over the 5 cycles shown in the Figure. Lui et. al. /29/ reported a similar observation, but with a general trend where a maximum wavelength was observed at one particular MLT and then decreased both toward earlier and later local times. The data here are consistent with those observations (the turn-around point being 18.3 MLT), but by themselves the observations are inconclusive. Auroral images from successive DMSP passes, used by Lui et. al. /29/ also suggest that the duration of the undulations lies between 0.5 and 3.5 hours. The auroral data prior to and following the observed undulations suggests a duration of about 5.5 hours : 921217 14:17:18 and 19:43:52. In all cases reported, the undulations occur near the peak development of storm ring current during a geomagnetic storm interval /29/.

The very high temporal resolution of this UV imagery allows one to investigate if the undulations propagate along the auroral boundary with time. Lui et. al. /29/ reported that the undulations were seen to bend toward the midnight region within a time period of about an hour. Mendillo et. al. /32/ also addressed this question with ground-based observation of undulations, which had a temporal resolution of about 6 minutes. It was concluded that the undulations observed in the ground based data set were fixed in location and varied only in amplitude over time. Although the time span is much shorter, this is also the case for the undulations found here. Over 6 second time intervals the crests of the undulations essentially remained stationary. Any motion of the crest seemed to be in the latitudinal direction, with a maximum change of .31 degrees. This observation in conjunction with previous observations suggests that the motion along the auroral distribution requires a time interval of about an hour before becoming evident.

Possible mechanisms which could be responsible for the observed undulations have been suggested by Lui et. al. /29/, Kelley /33/, Yamamoto et. al. /34/ and Yamamoto et. al. /30/. Essentially all proposals invoke the Kelvin-Helmholtz shear flow instability because of evidence of large amplitude electric field spikes (and hence shears) in the region just equatorward of the diffuse auroral boundary /35,36/. Such spikes tend to have maximum amplitudes on the order of 100 to 250 mV/m near the ionosphere and are directed poleward. Vinas and Madden /37/ extended the straightforward shear flow calculations to include the effects of concurrent interchange instability (ballooning instability) and determined an instability criteria for the region of the plasmapause. In analogy with hydrodynamic calculations involving the Rayleigh-Taylor instability a stability criteria was developed in terms of a magnetic Richardson number :

$$R_i = \frac{(\Omega_g{}^2 + k_{||}{}^2 v_A{}^2)(1 + k_{||}{}^2/k_{per}{}^2)}{(dv_\phi/dr)^2} \tag{4}$$

where Ω_g is the Rayleigh-Taylor frequency (evaluated at the plasmapause to be .036 rad/s /33/), v_A the Alfven speed and the k's represent the parallel and perpendicular wave numbers. The criteria for instability was found to be $R_i < .25$. Since what is normally observed are the field variations, the shear flow needs to be expressed in terms of the electric field using the frozen-in-flux assumption :

$$(dv_\phi/dr) = (1/B)(dE/dr) \tag{5}$$

The shear flow is presumed to be driven in the equatorial plane (or more reasonably at the position of minimum B field) and thus in order to relate this criteria to the observations presented here the effects of tracing along the magnetic field lines from the magnetosphere to the ionosphere must be included. Mozer /38/ presented a simple approach to this involving only the dipole field (reasonable here because of the low latitude of the undulations) and assuming no parallel electric fields. Under these conditions and using the L value of the dipole field lines to characterize their position :

$$\Delta E_x = 8L^2(L - \frac{3}{4})B_M \Omega_g \Delta x \tag{6}$$

Because of the similarity of the wavelength to those in discrete arcs noted above (see also /39,26/) the average wavelength is used to estimate the size of the shear zone : in this case 37 km. For the locations of the undulations presented here, using appropriate B field and L values one obtains a change in electric field over the shear zone of roughly 300 mV/m which is reasonably consistent with prior field observations.

Yamamoto et. al. /30/ suggest two possible mechanisms as sources of this periodic structure. Each source is proposed to produce the two types of undulations which they categorized. They propose Type I undulations result from the presence of a sub auroral jet located near the equatorward boundary of diffuse aurora, which excites Kelvin-Helmholtz waves. The second type of undulations, giant undulations, result from Kelvin-Helmholtz waves which have been excited by a polarized arc sheet. Both of these mechanisms have been simulated numerically and results have agreed with the observed undulations.

SUMMARY

The Freja UV Imager observations have shown many examples of periodic structures in both the discrete and diffuse auroras, a portion of which have been described. The discrete aurora commonly display counterclockwise rotational features and seem to be located throughout the auroral distribution. Relationships between the wavelengths and latitudinal extent of the distorted arc systems indicates that these forms are directly related to sheared flows which in turn are associated with plasma intabilities. As evident from the variety of features observed in the optical data, the plasma instabilities are capable of operating over extensive regions with widely separated vortical points. The intensities of the distortions along the arc reveals that there must be a variation in field aligned current density of the perturbations in the shear layer. The intensity variation along the arcs tends to indicate that the field aligned current density is greatest near the noon and midnight regions. Further analysis has shown that the longitudinal extent of downward field-aligned currents is on average roughly 3 times greater than that of the upward field-aligned currents. The undulations observed on the equatorward boundary of the auroral distribution also demonstrate the effect of shear flows. The dimensions of the undulations indicate that the production mechanism is larger in scale size than that of the discrete distortions. The wavelengths and amplitudes vary from cycle to cycle and seem to decrease toward the noon and midnight regions, indicating that the intensity of the production mechanism varies in the longitudinal direction. The observations over time indicate that the mechanism operates over long time periods and is essentially stationary. The undulations observed have been found to agree with the proposal of a Kelvin-Helmholtz shear flow instability as a source of production. When calculated from both experimental and theoretical approaches, the magnitude of the electric field spikes that accompany the instability are in agreement.

Optical observation of periodic structure within the auroral distribution indicate that a sheared flow associatied with plasma instabilities, operating over most regions of the auroral distribution in varying degrees, is responsible for the production of these forms.

ACKNOWLEDGEMENTS

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