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Intense Sheared Flow as the Origin of Large-Scale Undulations of the Edge of the Diffuse Aurora

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Using photographs from the DMSP satellite Lui et al. (1982) have found several examples of large scale undulations of the edge of the diffuse aurora. Several satellite experimenters have previously reported intense sheared flow near the edge of the diffuse aurora as evidenced either by detection of large localized meridional electric fields or by narrow regions of high azimuthal flow velocity. It is suggested here that the diffuse auroral undulations are caused by an instability of this sheared flow. In order to test this idea, a search for in situ satellite flow data associated with the events presented by Lui et al. was made. In addition the shear flow events reported by Rich et al. (1980) were used as a basis to search for near simultaneous DMSP photos. The cross-section of these data sets was not large. The closest example was a satellite pass indicating shear 20 minutes after a DMSP photo showing strong undulations which had been developing for at least an hour. A theory recently published by Viñas and Madden (1986) is in good agreement with the observations in that, (1) several of the events studied by Rich et al. satisfied the magnetic Richardson number criterion for instability and (2) the observed wavelengths are in good agreement with the theory. A recent numerical simulation by Pritchett (1985) also seems to support the concept that the edge of the diffuse aurora may be unstable to a shear driven process. An interesting feature of the analysis presented here is that when scaled from ionospheric heights to the equatorial plane, the shear frequency is only reduced by 30–40% from ionospheric values.

INTRODUCION

Lui et al. [1982] have reported several examples of large-scale undulations in the equatorward edge of the diffuse aurora. The events seem to have durations of 1–2 hours, occur in the evening time periods, and result in structures having horizontal wavelengths the order of 200–900 km.

The thesis of this paper is that such structuring is due to the large poleward electric fields which have been observed at the equatorward edge of the auroral oval in the evening sector. To be more precise, it is suggested that the undulations are a result of a shear instability in the plasma flow associated with the observed spatial variations in the electric field pattern. In situ observations of large electric fields in this zone were first reported by *Smiddy et al.* [1977] using S3-2 satellite data. Subsequent reports on the phenomena were made by *Maynard* [1978], *Spiro et al.* [1979] and *Rich et al.* [1980] using satellite borne electric field detectors or drift meters. *Unwin and Cummack* [1980] have also reported large drift velocities in the same local time and latitude range using ground based coherent scatter methods. *Gonzales et al.* [1983] also made brief mention of an incoherent scatter measurement in which the Millstone Hill radar detected a localized large azimuthal drift at roughly the right location, but no systematic study has been made with such radars.

The upshot of these studies is that very large localized meridional fields do form at the equatorward edge of the oval with ionospheric field strengths at 1300 km altitude as high as 350 mV/m corresponding to ionospheric flow speeds up to 10 km/s. The fields have been observed near the equatorial plane [*Maynard et al.*, 1980], have nearly conjugate features on the same low altitude satellite orbit [*Rich et al.*, 1980], and seem to be storm and substorm related.

In the next section we present results of a search for near simultaneous data from satellite electric field receivers and from DMSP photos, followed by a brief theoretical analysis based primarily upon the recent work of *Viñas and Madden* [1986]. The results of the search are not terribly convincing and a dedicated experiment is needed. Preliminary results of such a search using ground based radar [*Providakes et al.*, 1985] and ground based optics are quite encouraging [*Baumgardner et al.*, 1985].

DATA PRESENTATION

A study of this type suffers from the combined effect of the sporadic nature of the geophysical phenomenon of interest and the equally sporadic nature of the observation intervals. The starting point was the article by *Lui et al.* [1982] in which data was presented for six events showing large scale undulations of the diffuse aurora on DMSP photos. The satellite electric field investigators on vehicles S3-3, Atmosphere Explorer and ISEE were then questioned concerning nearby satellite passes. The ISEE and S3-3 searches proved fruitless since satellite data was not taken on the days studied by Lui et al.

The Atmosphere Explorer AE study was only slightly more informative. AE signatures indicating large electric fields were detected at 0821 UT on July 5, 1978 (16 hours after the event on that day reported by Lui et al.) and at 0628 UT on June 26, 1978 (14.5 hours before the event reported by Lui et al.). These event times for the large electric fields both occurred during the same magnetic storm which Lui et al. have associated with their events. The *AE* index they provided for June 26, 1978 shows a 700-γ deflection at the time of the Atmosphere Explorer satellite pass.

Turning the process around, the study by *Rich et al.* [1980] was used to identify in situ events and then the DMSP files were searched for near simultaneous photos. Of the seven events published by Rich et al., three had associated DMSP photos. A series of DMSP photos for September 19, 1976 are presented in Figures 1*a*–1*c*. The images are negative so dark portions correspond to the aurora. Sketches are included on the left-hand side to guide the reader's eye. At 0939 UT (Figure 1*a*) discrete arcs could be seen and the equatorward edge of the oval was quite smooth. At 1035 UT the aurora was quite widespread in the poleward region indicating that a substorm was in progress and a structuring at the equatorward edge of the diffuse aurora had started. In the next image (1121 UT) the equatorward edge of the diffuse aurora was well

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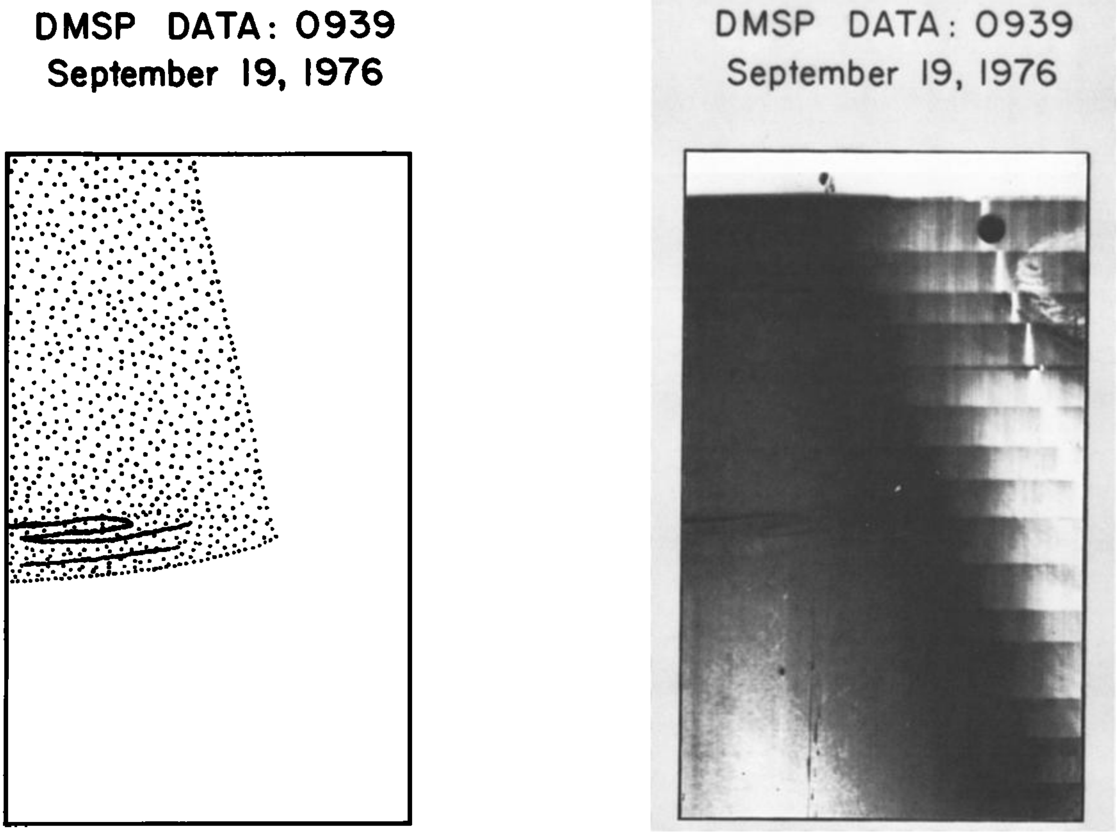

Fig. 1*a*. A DMSP photo taken on September 9, 1976 in the southern hemisphere. Several discrete arcs can be seen in the photo along with smoothly bounded discrete auroral emissions. The left-hand sketch here and in subsequent photos is meant as a guide to the reader's eye.

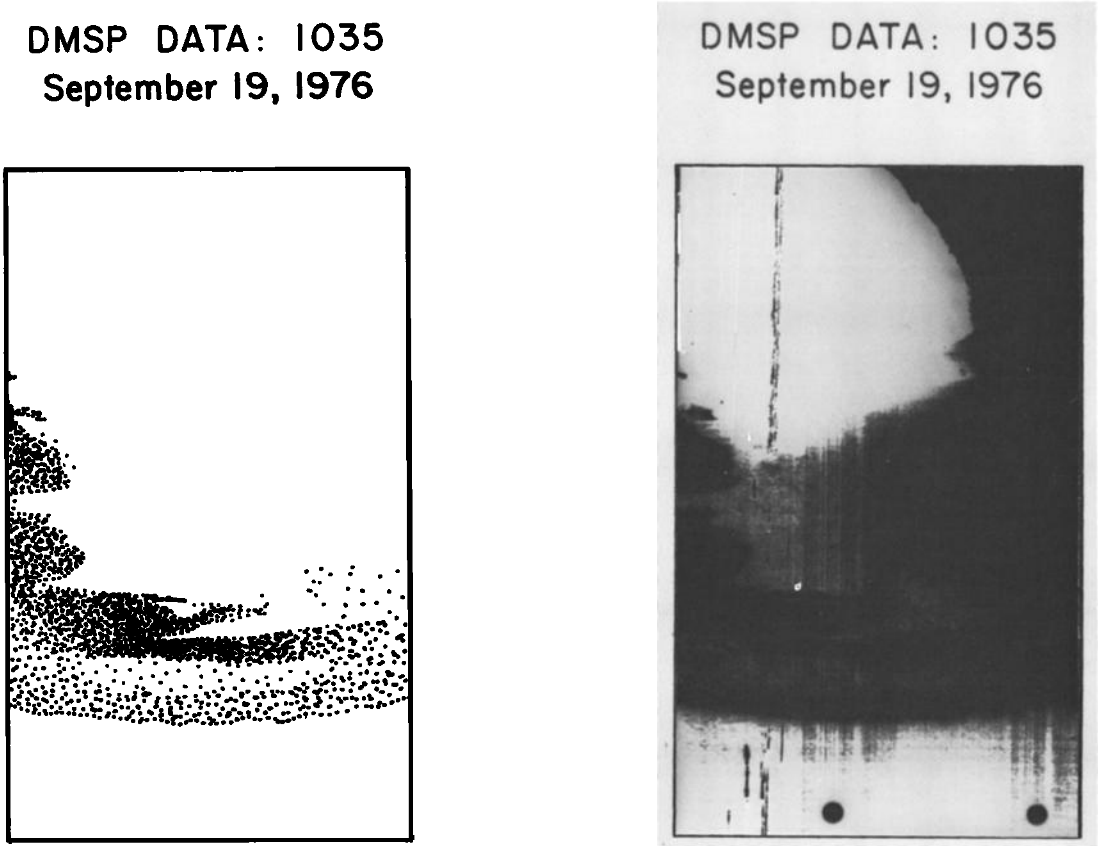

Fig. 1*b*. The DMSP photo on the pass subsequent to Figure 2*a*. Here is the discrete aurora is much more widespread and small sinusoidal oscillations of the boundary exist.

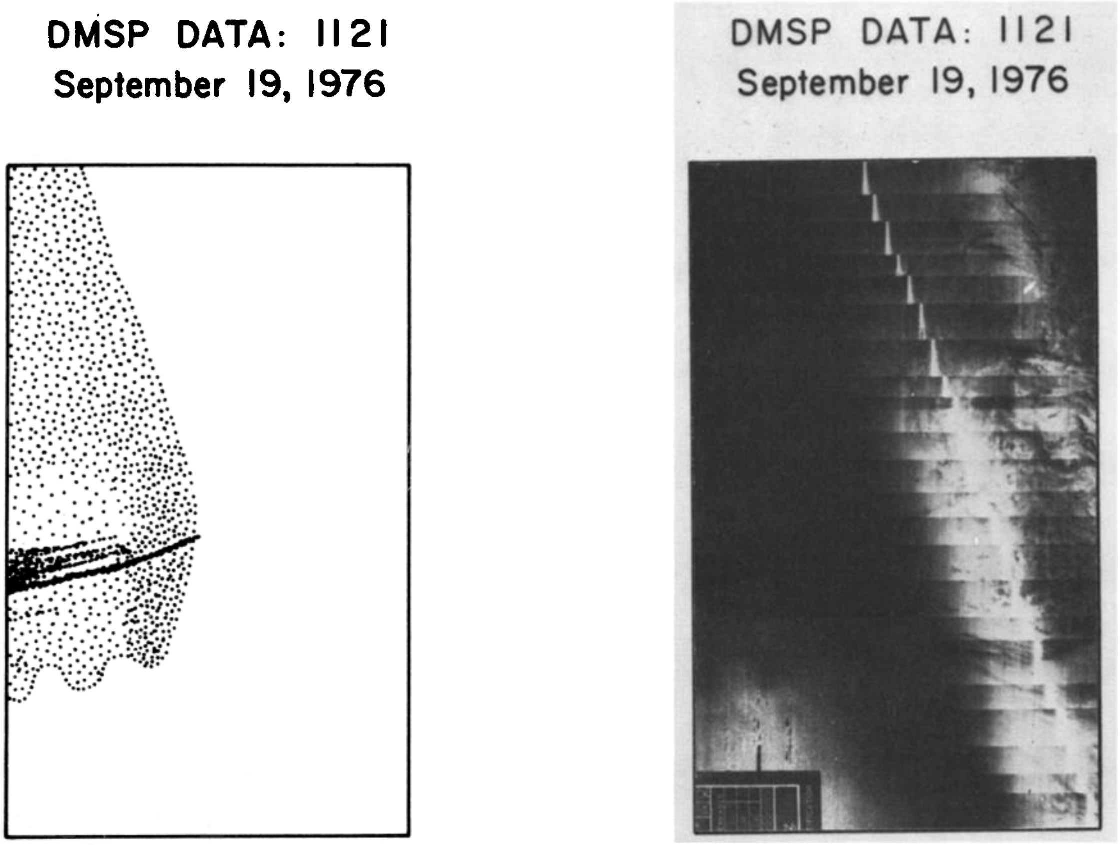

Fig. 1*c*. The DMSP photo on the pass subsequent to Figure 2*b*. Well developed undulations of the equatorward edge of the diffuse auroral arc now quite evident.

undulated in much the same manner as reported by Lui et al. As shown in Figure 5 of *Rich et al.* [1980] the S3-2 satellite passed through the latitude region of interest at 1151 UT. That plot is reproduced here as Figure 2 to show the existence of a large localized electric field spike exceeding 100 mV/m at an invariant latitude of 61°. This event is the nearest to simultaneous data found in the study, a 30 minute time difference. Since the events are long lived and since this one had not yet begun at 1035 UT, it is reasonable to assume that the diffuse auroral undulations coexisted with the satellite pass. Unfortunately, the next DMSP image is not available.

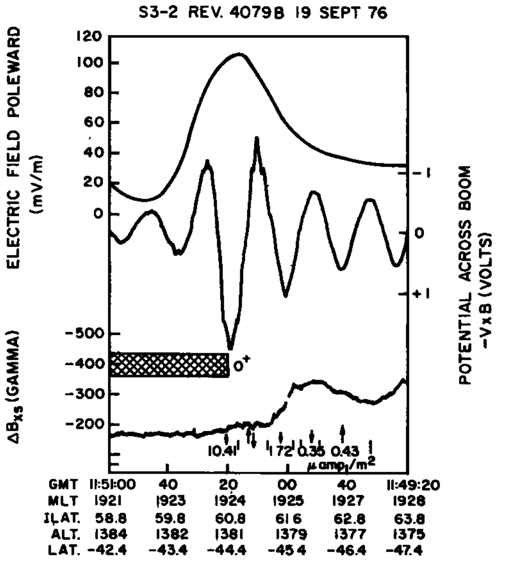

Fig. 2. Data from the S3-2 satellite showing a strong electric field near 60° invariant latitude. Note that the plasma composition near 1400 km change from O^+ to H^+ near the electric field spike. Field aligned current estimates are noted along the lower portion of the figure just below the perturbation magnetic field.

Auroral image data for May 2 and May 3, 1976 events are also presented in Figures 3*a*, 3*b*. Diffuse auroral undulations were detected at 1227 UT on May 2 and 0203 UT on May 3. The S3-2 data shown in Figure 4 bracket this interval since they were obtained at 0310 UT on May 2 and 0435 UT on May 3. Peak localized fields of 245 mV/m at 60.4° invariant latitude and 149 mV/m at 53.5° invariant latitude respectively were detected by the satellite detectors.

The results of this study are encouraging but not definitive. They have inspired some theoretical considerations which we describe below as well as some further experiments designed to produce simultaneous observations of shear flow and diffuse aurora [*Providakes et al.*, 1985; *Baumgardner et al.*, 1985].

DISCUSSION

Although not conclusive, the present study supports the hypothesis that large-scale undulations of the diffuse auroral boundary are related to a strong sheared flow at that boundary. Such flows often occur in geophysical fluids and can be unstable to the generation of large-scale perturbations in the flow pattern. A recent numerical MHD study by P. L. Pritchett (unpublished manuscript, 1985) shows formation of undulations in a sheared plasma flow which are visually quite similar to the undulations of the edge of the diffuse aurora. They find that the typical wavelength of the undulation perpendicular to the shear is roughly 10 times the characteristic size of the shear region. As noted below, this is in good agree-

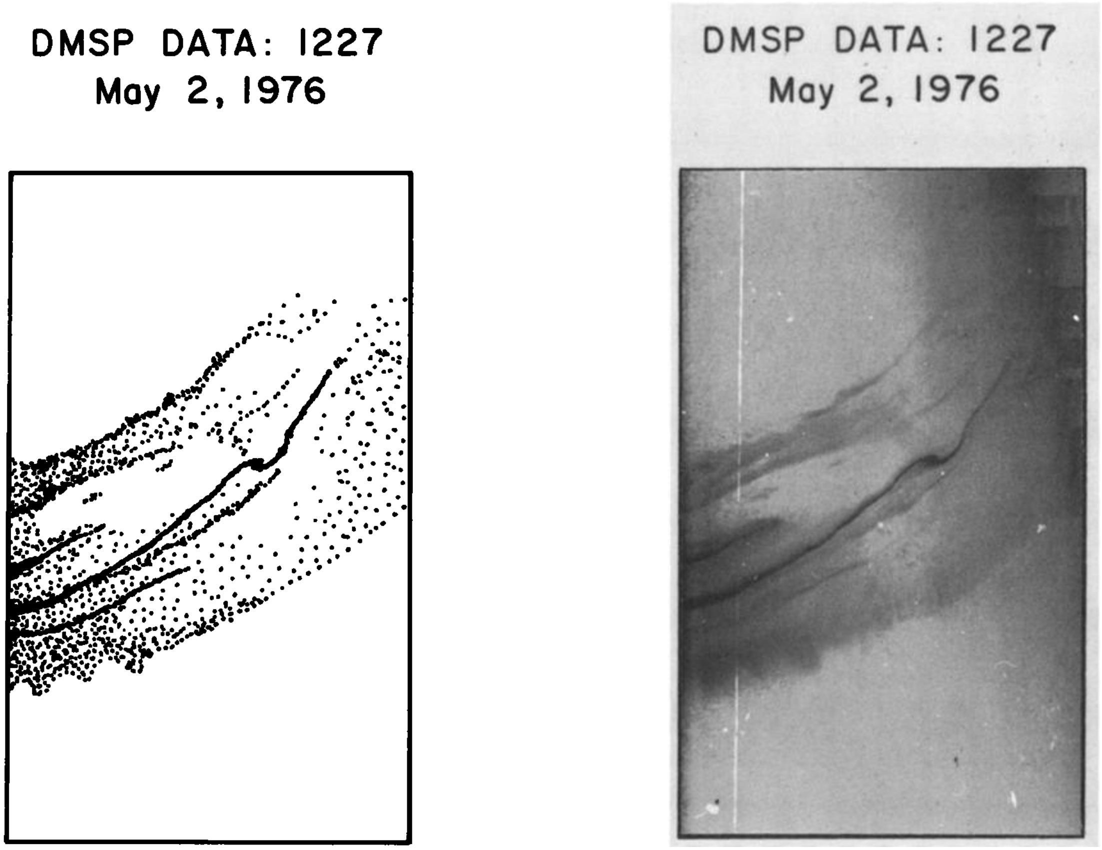

Fig. 3*a*. A DMSP photo taken on May 2, 1976 showing well developed undulations of the equatorward edge of the diffuse aurora.

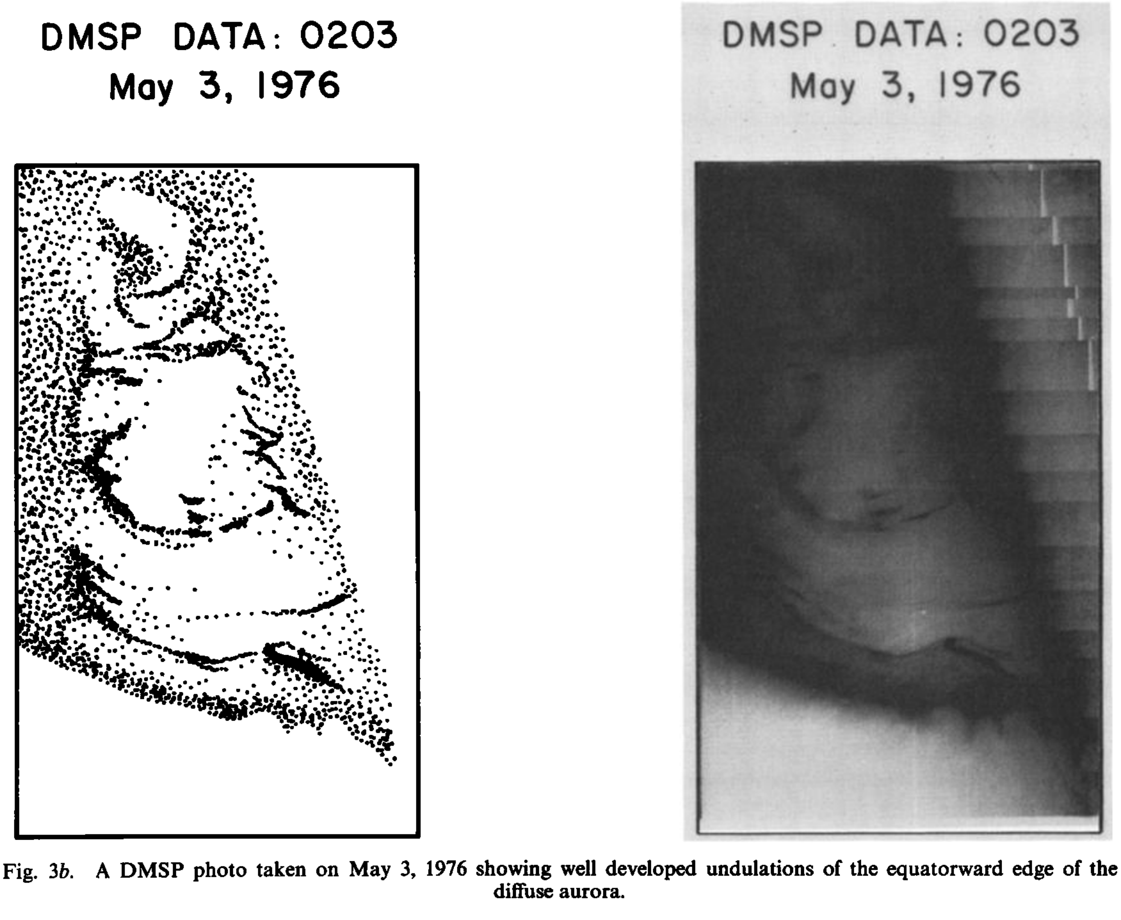

Fig. 3*b*. A DMSP photo taken on May 3, 1976 showing well developed undulations of the equatorward edge of the diffuse aurora.

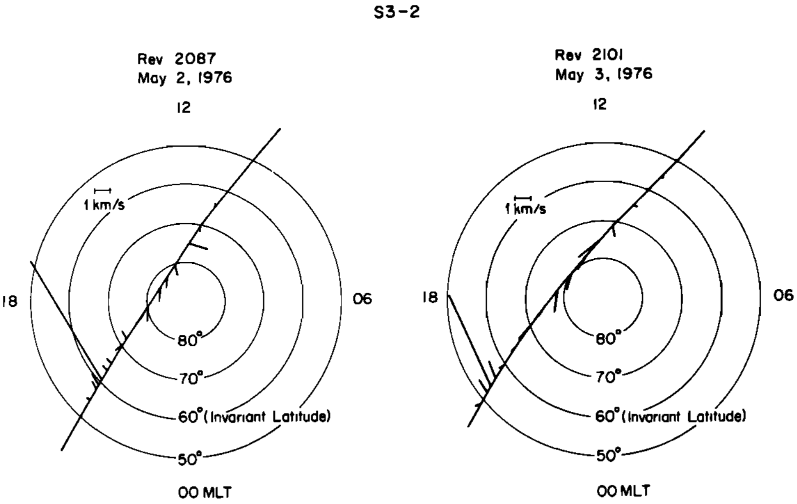

Fig. 4. Plasma flow vectors deduced from the S3-2 electric field receiver. The pass on the left occurred at 0310 U.T. on May 2, 1976 and the one on the right at 0345 UT on May 3, 1976.

ment with the observations by *Lui et al.* [1982] and with the observations reported here. The linear growth time quoted by P. L. Pritchett (unpublished manuscript, 1985) and by *Pritchett and Coroniti* [1984] corresponds to about 8 minutes which is also very reasonable.

The numerical results are encouraging but it is somewhat easier to compare the data with an analytic theory. To accomplish this, the recent work by *Viñas and Madden* [1985] is used as a guide. A crucial parameter in their analysis is the magnitude of the shear in the flow. This can be readily found at ionospheric heights from the polar orbiting satellite data. We use the term shear frequency since the units of dv/dx are $(\mathrm{s})^{-1}$. To transform these shear flows to the equatorial plane we use a dipole magnetic model and the frozen-in field assumption which is equivalent to considering the magnetic field lines as equipotentials. This seems quite reasonable since it is generally thought that the diffuse aurora is not accompanied by large field aligned potential drops. *Gonzales et al.* [1980] showed via simultaneous measurements in the equatorial plane (whistler duct drifts) and in the ionosphere (incoherent scatter) that the large-scale field near $L = 4$ does indeed map to the equatorial plane in a manner consistent with the equipotential condition and a dipole geometry. The conditions for the latter study were relatively active and seem appropriate to the situation here.

The shear frequency in the equatorial plane associated with each of the events published by *Rich et al.* [1980] was obtained as follows. In the ionosphere the zonal shear is related to the meridional electric field via

$$(dv_y/dx)_I = (1/B_I)(dE_x/dx)_I$$

For simplicity we assume the flow is L shell aligned so that the x direction is in the magnetic meridian. In the magnetospheric equatorial plane a meridional electric field maps into a radial electric field and the corresponding shear is

$$(dv_\phi/dr)_M = (1/B_M)(dE_r/dr)_M$$

The ratio, R, of ionospheric to magnetospheric shear is then

$$R = \frac{(dv_y/dx)_I}{(dv_\phi/dr)_M} = \frac{B_M}{B_I}\frac{(dE_x/dx)_I}{(dE_r/dr)_M} \cong \frac{B_M}{B_I}\frac{(\Delta E_x)_I}{(\Delta E_r)_M}\frac{(\Delta r)_M}{(\Delta x)_I}$$

Mozer [1970] has shown that for the equipotential field line assumption and a dipole field, the second and third ratios both vary as $2L(L - 3/4)^{1/2}$ and hence

$$R = (B_M/B_I)4L^2(L - 3/4) \qquad (1)$$

For the S3-2 satellite the data were obtained between 700 and 1500 km. Evaluating R for observation heights of 700 km and 1500 km respectively on a field line with an L value of 4, R ranges from 2.5 to 3.5. Thus the magnetospheric shear is only reduced by 30–40% from ionospheric values. Each event has an associated positive and negative shear since the electric field is localized. These two values were averaged to yield the shear frequencies given in Table 1. Both the ionospheric and magnetospheric shears are listed in the table.

Turning now to the analysis of *Viñas and Madden* [1985], they find that the Richardson number (R_i) criterion used in the analysis of atmospheric flows can also be defined in a sheared MHD flow. They define a magnetic Brunt-Vaisala frequency Ω_g via the expression

$$\Omega_g^2 = -g\frac{d}{dr}(\ln \rho_0) + \frac{(g + 2V_A^2/r)}{\gamma(1 + V_A^2/C_S^2)}\frac{d}{dr}(\ln p) + \frac{V_A^2}{C_S^2}\frac{(g - 2C_S^2/r)}{(1 + V_A^2/C_S^2)}\left(\frac{d}{dr}(\ln B) - 1/r\right)$$

where g is the gravitational field, ρ_0 the mass density, V_A the Alfven speed, γ the ratio of specific heats, C_S the sound speed and B the magnetic field. They show that instability occurs when

$$R_i = \Omega_g^2/(\partial v_\phi/\partial r)^2 < 0.25$$

which is analogous to criterion which pertains in atmospheric shear flows. They have applied their theory to the plasma-

TABLE 1. Shear Parameters

Day, 1976	Time, UT	Ionospheric Shear, s^{-1}	Magnetospheric Shear, s^{-1}	Richardson Number
Jan. 31	2201	0.031	9.7×10^{-3}	13.8
Jan. 31	2238	0.017	6.8×10^{-3}	2.8
March 28	0003	0.18	0.074	0.24
March 28	0509	0.42	0.17	0.045
May 2	0309	0.21	0.06	0.36
May 3	0436	0.21	0.060	0.36
Sept. 19	1150	0.025	0.017	4.5

pause region, and estimate that the magnetic Brunt-Vaisala period in that region is 174 seconds and hence $\Omega_g = 0.036$ rad/s. For $k_{11} = 0$, the critical shear value corresponding to $R_i = .25$ is then $(dv_\phi/dr) = 0.072\ \mathrm{s}^{-1}$. The Richardson number is also listed for each of the entries in Table 1. Two of the shear events have $R_i \leq 0.25$. Two more are quite close (0.36). For a k_{11} equal to the inverse of the length of the magnetic field line, as suggested by Viñas and Madden, the instability condition is modified and only the March 28 date remains unstable. Note, however, that our shear estimates are lower limits since the satellite trajectory is not likely to be exactly perpendicular to the flow, particularly after the medium begins to structure. Perhaps even more important is the fact that observations of plasma instabilities are usually made in the fully non linear state. Often this means that the plasma parameters are near to conditions of marginal stability. It thus seems that the strong shears observed near the equatorward edge of the diffuse aurora may be unstable to a shear flow instability.

Some feeling for the growth rate comes from the data in Figures 1*a*–1*c*. In the sequence of three photos spanning 2 hours, the edge of the diffuse aurora evolved from a featureless line to one with small sinusoidal variations (after 1 hour) and finally to one with a very well developed nonsinusoidal structure. *Viñas and Madden* [1985] find that the growth rate at the equatorial plane peaks in the range $\gamma^{-1} \approx 0.2(\Delta_m/u_0)$ where Δ_m is shear scale and u_0 is the magnetospheric flow speed at the peak of the layer. The ionospheric shear scales ranged from 30–300 km which map to the magnetosphere as $2L(L - 3/4)^{1/2}$ which corresponds roughly to the range 430–4300 km in the equatorial plane. Taking a peak ionospheric electric field of 200 mV/m yields γ in the range $10^{-2}(\mathrm{s})^{-1}$ to $10^{-3}(\mathrm{s})^{-1}$, which corresponds to growth periods of 100–1000 seconds, which are quite reasonable. The Viñas and Madden growth rate peaks at a zonal wavelength roughly eight times the thickness, Δ. The mapping factor from the magnetosphere to the ionosphere for large-scale zonal electric fields such as those which would be associated with these electrostatic perturbations is given by *Mozer* [1970] as $L^{3/2}$ which is also equal to $(8)^{-1}$ at $L = 4$. Thus, at ionospheric heights the theory predicts zonal wavelengths in the range 430–4300 km. The higher numbers here correspond to the events with large Richardson numbers and hence may not be relevant. At any rate the theory yields unstable wavelengths in agreement with the observations of *Lui et al.* [1982] and with the data presented here.

Finally as noted above, the studies by P. L. Pritchett (unpublished manuscript, 1985) and by *Pritchett and Coroniti* [1984] yield very similar values for growth rate and wavelength of maximum growth.

Lui et al. [1982] did discuss a Kelvin-Helmholtz shear driven process as a possible origin for the undulations and pointed out the shear associated with the difference between corotation and the mean magnetospheric flow. However, when the Richardson number criterion is applied, this shear is much too small for instability. The present analysis indicates that instability will only occur when large localized electric fields build up at the plasmapause. These fields are not yet completely understood but may be related to a zonal pressure gradient in the magnetosphere [*Smiddy et al.*, 1977] or to the penetration of hot ring current protons further equatorward then the electrons during magnetic storms and associated substorms [*Southwood and Wolf*, 1978]. This would result in a sporadic storm and substorm related occurrence of strong shears which in turn lead to structuring of the diffuse auroral edge.

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