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Spatial and temporal characteristics of giant undulations

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Abstract. A giant undulation event observed at SANAE, Antarctica (L = 4) is reported. During the event the geomagnetic activity was high, as was the case in previously reported observations of giant undulations. Data were recorded by all-sky and small field-of-view TV cameras, from 2346 UT on September 10, to 0007 UT on September 11 (MLT ~ 2200 h) 1987. The fine temporal and spatial resolution of the TV data made a detailed study of the undulation possible. The average wavelength was 170 km and the amplitude of the wave increased from 70 km to 140 km in 10 minutes. Wave propagation, measured at different positions on the undulation, was duskward with a phase speed of 540 to 650 m/s. An inner structure, propagating at a speed of 2.5 to 4.0 km/s, about 3 times as fast as the undulation form, was observed just poleward of the undulation boundary, indicating the presence of strong velocity shear. The linear theory of the velocity shear instability is examined as a possible generation mechanism on the basis of these observations.

1. Introduction

Large-scale undulations in the equatorial edge of the diffuse aurora were first reported by *Lui et al.* [1982]. They have duration times of 1 to 2 hours, occur in the evening sector during strong magnetic activity, and have horizontal wavelengths of the order of 200 to 900 km.

It has been suggested that the cause of these giant undulation events is a plasma instability due to strong velocity shear, often located near the equatorward edge of the evening side auroral oval [*Kelly,* 1986, and references therein]. *Kelley* [1986], from simultaneous DMSP satellite images and S3-2 electric field measurements, found a strong poleward electric field localized in latitude, i.e. a velocity shear. Simulation studies of the generation mechanism for these waves were reported by *Yamamoto et al.* [1991] and *Yamamoto et al.* [1993].

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A detailed knowledge of the propagation and growth of these waves is necessary to arrive at a suitable generation mechanism. However, most of the few previous studies are based on observations by the DMSP scanning imager from which it is not possible to identify the direction of motion or the development of the wave. *Providakes et al.* [1989] and *Mendillo et al.* [1989] also reported the characteristics of this giant undulation event from data obtained by 630 nm all-sky ground-based imagery. They did not find any systematic wave motion in their data.

In this paper we examine in detail one giant undulation event observed at SANAE, Antarctica. The characteristics of this event are presented, and special emphasis is given to the propagation and the temporal change in amplitude of the wave forms together with the inner structure of the wave. A possible generation mechanism is discussed on the basis of these characteristics.

2. Observations

The data used in this study are all-sky and small field-of-view (35° × 42°) auroral images recorded by ground-based TV cameras at SANAE, Antarctica (geographic latitude: 70.31° S, longitude: 357.60° ; corrected geomagnetic latitude: -60.4°, longitude: 44.2°). A giant undulation event was observed from 2346 UT on September 10 to 0008 UT on September 11, 1987. The TV cameras were used without filters and basically recorded white-light images of auroras. During this period the geomagnetic activity was high with Kp 6- and 5+ before and after 0000 UT respectively. The AE index registered strong disturbances from 2030 to 2300 UT with a peak value of 1200 nT. A high activity level of more than 500 nT continued until 0200 UT, thus indicating strong geomagnetic activity during the period of the giant undulation.

Figure 1 shows sequential pictures, every 3 minutes, of all-sky images between 2358 UT and 0007 UT. The images presented here are positive, so that white represents auroral light emissions. On each image north (equatorward direction) is at the bottom and the east is at the right. Wave structure can be seen on the northern edge of the broad diffuse auroral region for each figure, as indicated by the arrows. The bright region near the northeastern horizon is due to light from the rising moon and not auroras. The observations began

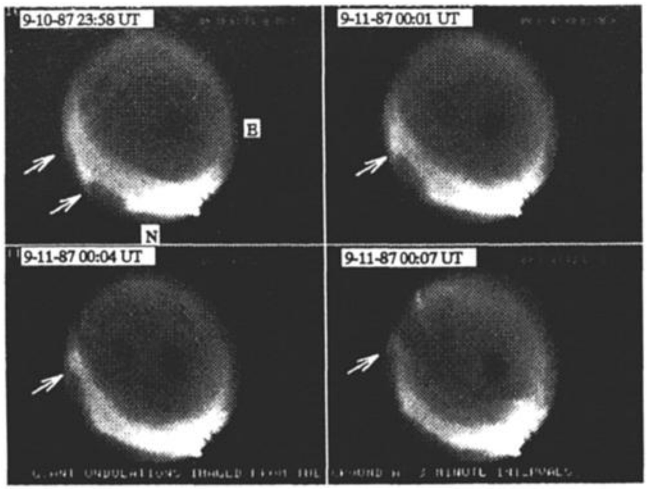

Figure 1. Sequential pictures, at 3 minute intervals, of all-sky TV images obtained at SANAE between 2358 UT and 0007 UT.

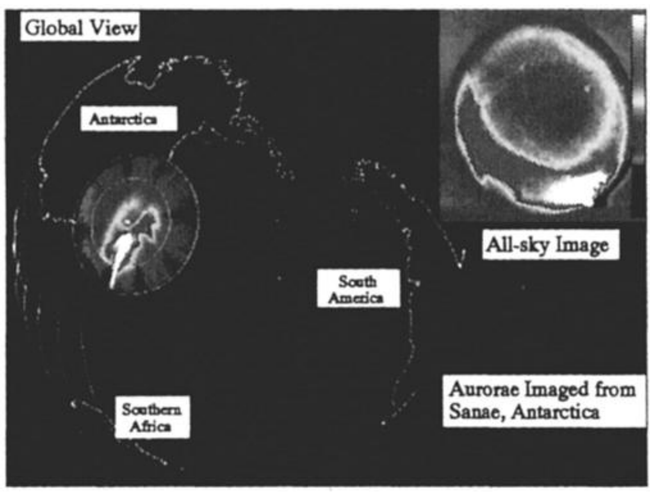

Figure 2. All-sky and projected images of giant undulation at 2358 UT.

from 2346 UT at which time the wave boundary was already evident, hence it is impossible to say when this event began.

It is clearly seen that one of the wave "peninsulas" (equatorward protrusion of aurora), of larger size than the rest, propagates westward along the equatorward boundary of the diffuse auroral region. The other wave peninsulas move in the same direction. Accurate estimates of the propagation speed can be obtained from these auroral image data.

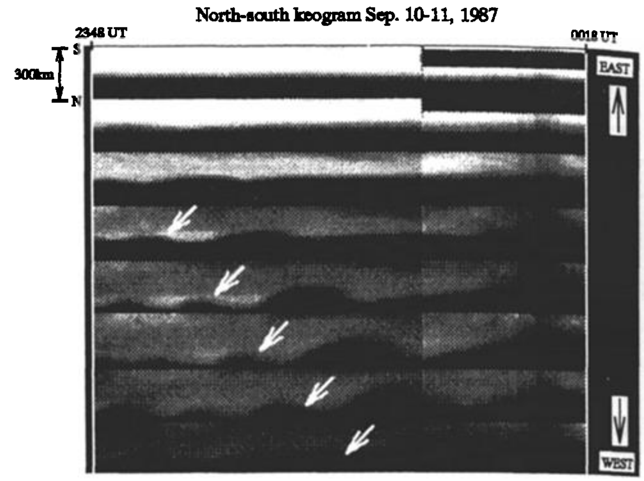

Figure 3. Auroral keograms sampled along eight lines across auroral region, as illustrated in Figure 2. The separation between each line is 1 degree in longitude. Each keogram corresponds to the temporal variation of auroral luminosity along the north-south line of 300 km although the scaling factor for each line is different because of technical problem of transformation. The westward motion of the wave form is indicated by the arrows.

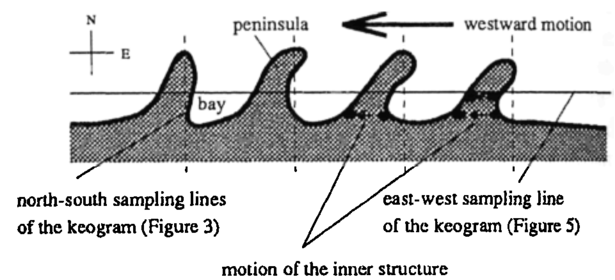

Figure 4. Schematic view of the observed giant undulation.

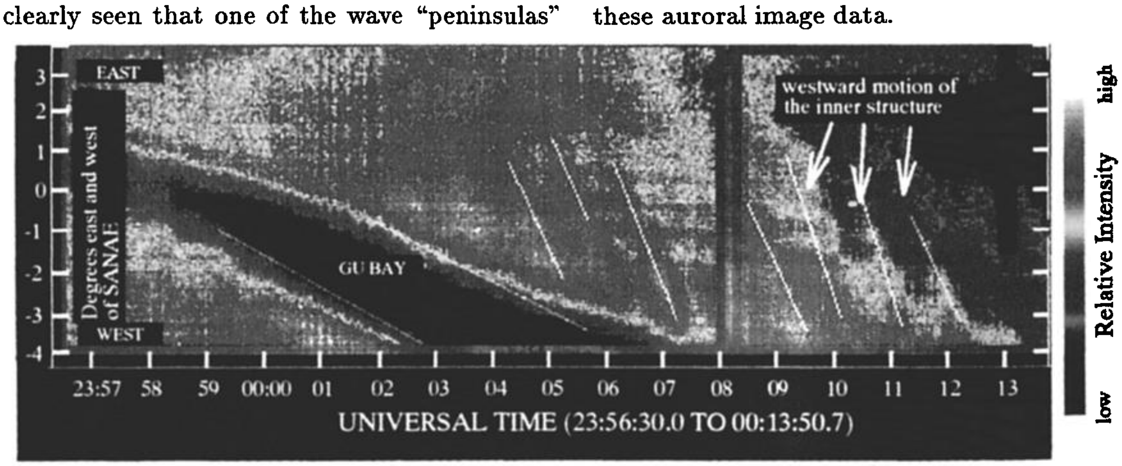

Figure 5. Auroral keogram sampled along two lines along the wave forms, as illustrated in Figure 4. The westward motion of inter structure is clearly seen as indicated by white lines and white arrows, together with that of bay structure. The speed of these inner structure is measured to be 2.5 to 4.0 km/s.

The configuration of the peninsulas becomes clearer if mapped onto ionospheric coordinates, as shown in Figure 2. Here the heights of auroras are assumed to be 100 km. Peninsulas are clearly seen on the transformed image, about 300 km north of SANAE Station. Wave peninsulas were also recorded on the small field-of-view camera, from which we can see the smaller-scale structure of the wave (data not shown). The wave form is rather stable, has no vortex structure, indicating the typical characteristics of diffuse aurora.

To measure wave speeds and amplitude growth, we show in Figure 3 so-called auroral keograms, the profiles of auroral luminosity along eight sampling lines across the diffuse auroral band versus universal time. The locations of sampling lines are schematically shown in Figure 4. These lines are separated by 1 degree intervals in magnetic longitude. The height of these auroral forms is assumed to be 100 km.

The passage of four wave peninsulas is recorded in Figure 3, each propagating westward so that they appear at later times in the lower keograms as indicated by the arrows. The propagation speed of the peninsulas is between 540 to 650 m/s, depending on each particular peninsula and the period. In addition, there is growth of the amplitude of each peninsula. If we focus on the first peninsula, the amplitude grows from 70 km at 2348 UT to 140 km at 0000 UT. The characteristic growth time is estimated to be about 700 seconds.

Figure 5 shows the result for an auroral keogram of the luminosity profile sampled along the east-west line crossing the undulation boundary, as illustrated in Figure 4. It is seen that there are inner structures just poleward of the undulation boundary (inside the bay region), propagating about 3 to 5 times as fast as the undulation itself. This indicates the presence of strong velocity shear. This westward speed (2.5 km/s to 4.0 km/s) is consistent with the electric field value of 100 to 250 mV/m around the undulation region obtained by *Kelley* [1986], assuming that $V = \mathbf{E} \times \mathbf{B}/B^2$ and $B \sim 4 \times 10^4$ nT.

A characteristic signature of the wave forms is that wave peninsulas are slanted toward midnight and the area of the bay is larger than that of the peninsula, as illustrated in Figure 4. Similar characteristics were also pointed out by *Yamamoto et al.* [1993]. Hence, we can conclude that the phenomenon described here is that of giant undulations as reported in previous studies.

It should be noted that the speed is measured in a coordinate system fixed to the earth and contains the earth's rotation effect. The earth's rotation speed at the latitude of the observations (70° S) is about 160 m/s. This effect, due to the earth's rotation, is substantially less than the wave speed of 540 to 650 m/s, and the speed of inner structure of 2.5 to 4.0 km/s.

3. Discussion

The characteristics of the giant undulation event, recorded by ground-based TV cameras, are summarized in Table 1. They are important because previously there has been very little known of the temporal variation of these wave forms, i.e. the propagation and growth of the wave. Such parameters are essential to any discussion of wave generation mechanisms.

The most remarkable finding in this study is that there are inner structures inside the bay form, propagating westward (duskward) with the velocity of 2.5 to 4.0 km/s. This structure cannot be found in DMSP images, or all-sky cameras with long-time exposure. This westward motion is consistent with the electric field values reported by *Kelley* [1986], indicating the strong evidence for the existence of the velocity shear region around the giant undulation region.

We also observe the westward (duskward) motion of the wave forms. This result is not in agreement with *Mendillo et al.* [1989], who observed no significant longitudinal motion. One possible explanation is that the diffuse auroral boundary is not always located close to a strong velocity shear region. Hence, their boundary of diffuse aurora observed by TV cameras at 630 nm, might not be located close to the strong velocity shear, as it was in this study. Another possibility is that their wave amplitude decreases in time while ours increases, so that our example is characteristic of the wave development during the strong shear flow, while theirs is typical of the decaying wave without energy supply due to shear flow.

We have made a comparison with the predictions of the linear theory of velocity-shear instability [*Ganguli et al.*, 1988; *Yamamoto et al.*, 1993]. According to the linear theory, for the most unstable mode the wavelength λ and wave growth rate γ are given by:

$$\lambda \sim 7.0\, a; \gamma \sim 0.16\, U_m/a$$

Here a and U_m are shear scale in the velocity profile and maximum flow speed, respectively. If we assume that the motion of the inner structure represents the maximum flow speed, the typical value of U_m is 3 km/s. We cannot determine a reliable value of a because we have very little information on the latitudinal distribution of the wave speed. Based on the observation by

Table 1. Summary of the observed characteristic features of giant undulation.

Item	Characteristics
Period of observation	2346 to 0008 UT (2200 to 2230 MLT)
No. of sequential peninsulas	4
Motion of the wave	540 to 650 m/s (westward)
Motion of the inner structure	2.5 to 4.0 km/s (westward)
Wave length	~ 170 km
Wave amplitude	70 km (2348 UT) → 140 km (0000 UT)
Shape of the wave form	Peninsulas *point* toward midnight (Bay area) > (Peninsula area)

Kelley [1986], a is 30 to 300 km, and from the above expressions λ is 210 to 2100 km, and γ^{-1} is 210 to 2100 s. Our observation indicates $\lambda \sim 170\ km$. If we take the shear scale value as 100 km, which is comparable to the wave amplitude and the mean value observed by *Kelley* [1986], and insert this value into the second expression $\gamma \sim 0.16\ U_m/a$, we obtain a growth time of $\sim$ 200 s. This value is rather small in comparison with the actual growth time of 700 s. Hence the expressions above, derived from linear analysis, might not be applicable, for the conditions for which the undulations reported here were observed. On the other hand, if the wave velocity itself represents the flow speed, the typical value of U_m becomes 0.6 km/s. As a result we get the calculated growth time of 1000s, and the linear theory is more consistent with the observation. However, in that case we must consider the other mechanism for generating the high-speed motion of the inner structure.

The mechanism for generating the localized velocity shear (or equivalently, poleward electric field) is a rather complicated process caused by magnetosphere-ionosphere coupling and has been discussed by several papers (*Providakes et al.* [1989] and references therein). By using the radar and the satellite data, *Providakes et al.* [1989] confirmed the presence of the ionospheric F layer density trough collocated with the localized electric field, and also proposed that the electric field is due to a thermoelectric generator driven by ion temperature gradient. *Yamamoto et al.* [1993] proposed a candidate model to systematically explain the formation of ionospheric plasma trough and the enhancement of poleward electric field. Although we do not have enough data to fully discuss the cause of the electric field, our data shows that the localized flow around the undulation form is maintained at least about 10 minutes.

Yamamoto et al. [1993] discussed the mechanism of generating wave forms with large wave amplitude comparable to the wave length. They concluded that a three current sheet system is necessary to generate such large wave forms. Unfortunately, for the event described here, wave amplitude stayed smaller than the wave length for most of the observation, because the undulations had propagated beyond the field of view of the camera before they grew sufficiently in amplitude.

4. Conclusion

We have described the characteristics of a giant undulation event in the equatorward edge of diffuse auroral region from ground-based optical imaging. Some of these characteristics, such as wave propagation speed and growth rate, have been measured for the first time. The presence of the high-speed inner structure inside the wave structure gives strong support to a generation mechanism based on the theory of velocity-shear instability.

It was not possible to determine the long term development of the instability because of the limited period during which the wave forms are in the all-sky field of view of the TV camera. Further observations will be required to discuss the nonlinear effect of the wave growth which can produce larger wave forms [*Lui et al.*, 1982; *Yamamoto et al.*, 1993]. Such observations will require a network of ground-based all-sky TV cameras to image giant undulations on the apparently rare occasions on which they occur.

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