Observed Microstructure of Auroral Forms

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Discrete auroras are primarily composed of linear elements, whereas diffuse auroras appear in a variety of shapes. Dynamical variations within discrete auroras are characterized by shear, evidently caused by field-aligned currents and charge excesses. In contrast, diffuse, pulsating aurora exhibits little shear, indicating lack of large currents and electric fields associated with this type of aurora.

1. Introduction

An inherent characteristic of most auroral forms is their highly structured nature. No general explanation for the structure exists, though two statements by ALFVÉN (1972) seem pertinent, "Space plasmas have often a complicated inhomogeneous structure" and "Currents produce filaments or flow in thin sheets."

Since the introduction of sensitive imaging systems for auroral observation about 15 years ago, it has been possible to record the often highly transient microstructure within auroras, though the great speed of the variation and weakness of some of the emitting structures presses to the limit the spatial (of order 1 mrad) and temporal (1/60 sec) resolution of devices now in use. This review deals mainly with observations with such imaging systems and also photographic cameras that have been made from the ground or aircraft by Canadian, Japanese, Soviet and American groups. In dealing with the dynamical morphology of auroral microstructure, these groups have emphasized relative measurements of intensity versus two spatial dimensions and time with only secondary importance being attached to observations of absolute intensity. Other imaging observations emphasizing measurement of absolute intensity have been made by S.J. Mende of Lockheed Palo Alto Research Laboratories.

A major difficulty in observation of auroral microstructure is caused by the alignment of the height extent of auroral forms along the direction of the local magnetic field. Exact determination of the shape of an auroral form from one observing point on the ground below can be accomplished only if the form is precisely in the magnetic zenith. Departure of the form by only a few degrees from the observer's magnetic zenith creates such a different perspective that errors in shape recognition and description are likely. This general difficulty makes it nearly impossible to accurately describe an entire auroral form, since virtually any form observed in the magnetic zenith extends, in at least one horizontal direction, well outside the zenith. Thus in describing the auroral microstructure, we are usually limited to those parts of the forms that lie near the zenith rather than entire forms.

We are concerned here with auroral shapes, developments from one shape to another, spatial motions and temporal variations. In considering the motions, it is natural to ask what is moving and what causes the apparent motion. Though it is now known that apparent auroral motions are caused by motions of the distant source region from which precipitating auroral primaries derive (i.e. 'successive dumping'), by motions of entire magnetic flux tubes feeding particles into the atmosphere ($E \times B$ motion) and by tipping of the flux tubes, it is impossible to tell from the observed apparent motions alone which type of motion is occurring. Therefore it is useful to bring into the interpretation of observed motions results obtained by other observations, particularly those of electric fields obtained by direct probe measurements or by the introduction of visible tracer ions above auroras.

2. Major Types: Discrete and Diffuse Auroras

Since the advent of topside imagery of auroras by the ISIS-2 (LUI and ANGER, 1973) and DMSP (PIKE and WHALEN, 1974) satellites it has become common to refer to 'diffuse' and 'discrete' aurora because the topside images show two regions of auroral precipitation aptly described by these terms. Least one become misled by these terms, it is necessary to recall that ground-based imaging observations show that both discrete and diffuse auroras can be highly structured. The primary distinction seems to be that diffuse auroras, even if structured, lack the high intensity and shear phenomena exhibited by 'discrete' auroras. Whereas 'diffuse' auroras have a variety of shapes ranging from linear to highly irregular, complex structures, the basic form of the 'discrete' aurora is linear. At times, the linear elements become highly distorted, but the basic linear characteristic remains.

3. Discrete Auroras

3.1 Shapes

Since the elemental shape of discrete aurora is linear it seems useful to retain the term arc for these structures and to give a new definition of an auroral arc based upon our current knowledge:

An auroral arc is the recognizable luminosity resulting from the impingement of a field-aligned sheet beam of electrons (or other charged particles) upon the atmosphere, the luminosity being approximately proportional to the energy deposited by particles in the energy range 100 eV to 100 keV. The lower border of the arc is sharp, in consequence of increasing atmospheric density with depth; it has an altitude, typically 80 to 300 km, defined by the maximum energy of the particles in the primary beam. The vertical extent to the diffuse upper border of the arc increases with the range of particle energy in the primary beam; the range varies from a few kilometers to more than 100 km. Arcs range in width from a few tens of meters to more than 1 km. They extend in length from of 100 km to thousands of kilometers. Their curvature ranges from slight to highly contorted.

This definition emphatically states that one can interpret the position, shape and intensity of an observed auroral arc in terms of the causative incoming particle beam. Also the definition is broadly enough stated to incorporate a number of forms listed in the Photographic Atlas of Auroral Forms (IUGG, 1963)—arcs, bands, draperies, partial corona and, as we shall see later, even rays. In light of current knowledge of causative processes there seems no reason to retain distinction between these different form types except for convenience of describing visual observations.

MAGGS and DAVIS (1968) measured the widths of 581 linear discrete and diffuse auroral forms as ranging from the instrumental cutoff at 70 to 4,440 m with the median width being 230 m. Experiments using rocket-borne electron accelerators (DAVIS *et al.*, 1971; HALLINAN *et al.*, 1977) indicate that minimum widths may be as small as 30 or 40 m, a few times the electron gyroradius. It is common to observe several narrow arcs spaced close together so as to appear as a single structure when viewed well off the direction of the local magnetic field. Though the individual arcs within such an ensemble may behave somewhat independently, discrete auroras never cross one another; hence, the ensemble may deform or drift as a unit.

3.2 Motions and deformations

The basic linear elements of discrete auroras are observed to undergo rotational

Fig. 1. At top, an all-sky photograph showing an auroral spiral which contains curls (auroral rays) along the arm leading to a second spiral in the east. At bottom, a TV image of several interconnected curls in the aurora.

developments which temporarily perturb the shape or cause major changes in shape. The rotational development having the largest scale size is the spiral, a vortex street structure ranging in size from 20 to 1,300 km (DAVIS and HALLINAN, 1976). HALLINAN (1976a, b) has shown the spiral to be an equilibrium configuration that develops when the current density exceeds approximately 10^{-5} amp m^{-2} in a field-aligned current sheet. Spirals in both the north and south hemispheres are clockwise (viewed antiparallel to the magnetic field direction $\mathbf{B}$, a convention followed throughout this paper) indicating upward current; they both windup and unwind, i.e. they are reversible. One wishing to associate measurements made at two different altitudes on a magnetic field line threading discrete aurora should take special note of the fact that the development of a spiral shifts the orientation of the magnetic field enough to cause the feet of the field lines to be displaced up to half the spiral diameter (i.e. 10 to 650 km).

Similar to spirals in appearance are the much smaller vortex streets called curls, as described by HALLINAN (1969), HALLINAN and DAVIS (1970), and OGUTI (1974). Curls are of order 1 km in diameter, they are always counterclockwise and are irreversible. In contrast with the spiral equilibrium structure, curls are the result of instability in a charge sheet; the rotation sense indicates negative excess charge at the point about which the curl forms. Seen end-on curls are auroral rays. HALLINAN (1976b) notes that curls and spirals can occur in the same auroral form, as in Fig. 1, along with folds, which exhibit a clockwise rotation sense and, like spirals, are reversible. As shown in Fig. 2, folds are of intermediate size between curls and spirals.

Fig. 2. Drawings of the cross sections of auroral arcs illustrating three major rotational distortions: spirals, curls and folds. The spirals and folds are clockwise, and the curls are counterclockwise. After HALLINAN (1976b).

HALLINAN (1976b) attributes folding to the current sheet mechanism and states that they occur at scale sizes where there is conflict between the counterclockwise shear of the charge sheet and clockwise shear of the current sheet such that the formation of spirals is suppressed.

It is not certain that all deformations to discrete auroral structures can be attributed to the charge sheet and current sheet shearing mechanisms discussed by Hallinan. One complex repetitive deformation occurring in the few minutes near the auroral breakups is the pulsing phenomenon called flickering (BEACH *et al.*, 1968). Sometimes visible by eye, flickering is a 10-Hz fluctuation in which field-aligned emitting elements seem to expand and contract and move erratically back and forth, but rotational motion appears to be involved. The variation has been detected by 42-MHz radar (SOFKO and KAVADAS, 1969).

Extensive observations of small-scale auroral deformations by OGUTI (1975) indicate the frequent occurrence of a deformation he has termed splitting (see Fig. 3). Figure 4 shows another example of such a development documented by DAVIS (1965). I have noticed that this deformation is likely to occur where there is a change in curvature of an arc, so it, too, may be the result of competing shear attributable to the charge sheet and current sheet mechanisms.

The observed rate of development of curls requires small-scale, transient horizontal electric fields sometimes as large as 1 V m^{-1} . Motions of rays along the arcs and relative motions of adjacent auroral arcs (Fig. 5), imply an inward-directed electric field in association with each arc, the motion being to the east on the north

Fig. 3. Schematic illustrations by OGUTI (1975) of various apparent deformations to auroral arcs. Parts A and B show the splitting deformation.

Fig. 4. An example of splitting observed near the magnetic zenith at Fort Churchill that led, within a few seconds, to the folded configuration at right. After DAVIS (1965).

Fig. 5. The pattern of longitudinal motion observed in close-spaced, active auroral arcs. The pattern implies an inward-directed electric field in association with each arc and which extends well beyond the arc.

of the center of an arc array and to the west on the south of the center. The large electric fields implied are not observed in the ionosphere but they do occur at altitudes greater than 4,000 km above the arcs (WESCOTT *et al.*, 1976). The apparent existence of these curiously high transverse electric fields led, in part, to the development of the *V*-shock equipotential model proposed by SWIFT *et al.* (1976) which now appears to explain most features of discrete auroras. Recent satellite-borne observations of high electric fields (MOZER *et al.*, 1977) and upward streaming positive ions above auroras (SHELLEY *et al.*, 1976) lend further support to the *V*-shock model.

4. Pulsating Aurora

Together with the diffuse background in which it appears, pulsating aurora is a major part of the display and represents a substantial fraction of energy input during a substorm. Whereas the characteristics of discrete aurora appear to form a cohesive understandable whole, the known characteristics of pulsating aurora seem chaotic and without obvious interpretation. Another contrast is in the complete lack of shearing phenomena within the pulsating aurora, whereas shearing develop-

ments are inherent in discrete aurora. The lack of shear in pulsating aurora does imply that substantial electric fields do not play a role in creating pulsating aurora.

Investigations, largely photometric, that have described the periodic variations in pulsating auroras are cited by OMHOLT (1971) and VALLENCE JONES (1974). Studies that have emphasized the shape, motions and detailed temporal changes in pulsating auroras using imaging data are those of CRESSWELL and DAVIS (1966), SCOURFIELD and PARSONS (1971), OGUTI (1975), ROYRVIK (1976) and ROYRVIK and DAVIS (1977).

A pulsating aurora is defined by ROYRVIK and DAVIS (1977) as one whose maximum intensity never exceeds ~ 10 KR in N_2^+ 1NG 4278Å and which undergoes at

Fig. 6. Schematic models of the auroral arc, at left, and of pulsating aurora. Indicated below each drawing is the horizontal electric field associated with each structure. The pulsating form is shown to extend downward from a diffuse background emission. At bottom, all-sky photographs show the differing appearance of the two types of aurora, and the DMSP image indicates occurrence along the auroral oval.

least one full cycle wherein there is first a rapid increase in intensity and then a rapid decrease, an additional restriction being that the horizontal drift motion of the modulated form differs little from the drift of nearby forms. Pulsations occur in arc and arc-like forms and in patches of irregular shape, the size and shape remaining unchanged as the form pulses on and off or growing and contracting (SCOURFIELD and PARSONS, 1971; ROYRVIK and DAVIS, 1977). Quasiperiodic variations in the range 0.05 to 2 Hz also are complex, a given form can change from one type of temporal behavior to another, and adjacent forms can display disparate behavior. Pulse shapes vary from widely-spaced half-sine waves to closely-packed square waves. Clear-cut trends with latitude, local time or whatever time have not been found. This failure and the major difference in behaviors of proximate forms suggest that the cause of pulsating aurora is linked to parameters that describe the plasma and field quantities on the particular magnetic flux tube occupied by the pulsating form. Recent observations by STENBAEK-NIELSEN *et al.* (1977) show that some pulsating auroras have very limited height extents, much more limited than is implied by Fig. 6.

5. Black Aurora

More than a curiosity, 'black aurora' is a lack of emission in well-defined regions within auroras which are essentially intermediate between 'diffuse' and 'discrete.'

Fig. 7. Television images of 'black aurora,' void regions in a field of relatively uniform auroral emission. The vortex street in parts A and B is clockwise seen antiparallel to B, indicating an excess of positive charge in the black void region. After ROYRVIK (1976).

These auroras are intermediate both in the sense that they occur in the transition from one type to another (especially diffuse to discrete) and the auroras exhibit a degree of shear behavior intermediate between that of diffuse and discrete aurora. The black void areas, in the form of thin ribbons or elongated elliptical holes drift east after midnight and west before (NAZARCHUCK, 1975). Comparison of our observations with those of NAZARCHUCK (1975) and OGUTI (1975) suggests that the black auroras appearing in the transition from discrete to diffuse aurora at the end of the substorm expansion phase may differ from those observed near the end of the recovery phase. Figure 7, after ROYRVIK (1976) shows examples of the latter type. The row of holes is of particular interest—these clearly are a vortex street structure similar to curls, but they show clockwise rotation and thereby imply an excess of positive space charge in the holes, i.e. outside the normal electron aurora.

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