OBSERVED CHARACTERISTICS OF AURORAL FORMS

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(Received 16 May, 1978)

Abstract. Observations indicate that the extended auroral arc is the basic form of the discrete aurora, the brightest and most obvious kind of aurora. Both motions of auroral arcs and their distortions into convoluted forms indicate the presence of shear processes involving substantial charge excesses and magnetic field-aligned currents. Consequently, strong electric fields, both horizontal and vertical, characterize the discrete aurora. The observations of auroral arcs and observations of associated charged-particle fluxes, electric fields and currents fit together into a relatively cohesive description of the auroral arc which is compatible with at least one proposed model of the causative processes. On the other hand, an equally important type of aurora – pulsating aurora – exhibits quite different characteristics which distinguish it from the discrete aurora and which are difficult to interpret satisfactorily in terms of existing proposed models of particle precipitation and excitation of auroral emission. The lack of shearing behavior in the pulsating aurora indicates that substantial electric fields are not associated with it. Transitional forms of auroras exhibit an intermediate degree of shear motion.

1. Introduction

In recent years the application of two distinctly different types of imagery to auroral observation has greatly increased understanding of the dynamical morphology of the aurora. The application of television techniques to auroral imagery obtained from ground- and aircraft-based platforms has allowed documentation of the rapid variations in auroras and the morphology of auroral structures in the range from a few tens of meters to several hundred kilometers. Very-large-scale images of the aurora have been obtained looking downward from the Isis 2 (Lui and Anger, 1973) and DMSP (Pike and Whalen, 1974) satellites. Whereas this form of auroral imagery provides informative global views of the aurora (see Figure 1), the temporal resolution is a factor of 10^5 lower than with the television imagery; i.e., the satellite images are obtained at the rate of one per 100-min orbit and the television images are obtained at the rate of 60 per sec.

Both types of auroral imagery have had profound effects upon our conception of what the aurora is like and both have modified the terminology in common use. The finding from the Isis 2 images that there usually appeared to be a weak and diffuse zone of aurora lying at the low-latitude edge of, or separated from, the zone of bright, discrete auroras led to the names 'diffuse' and 'discrete' for the two types of aurora. These terms were rather natural since, to the eye at least, the weak aurora in the lower-latitude zone did appear much more diffuse and ill-defined than the bright sharply defined forms observed in the evening sector of the auroral oval and along its high-latitude boundary in the morning sector.

Space Science Reviews **22** (1978) 77–113.

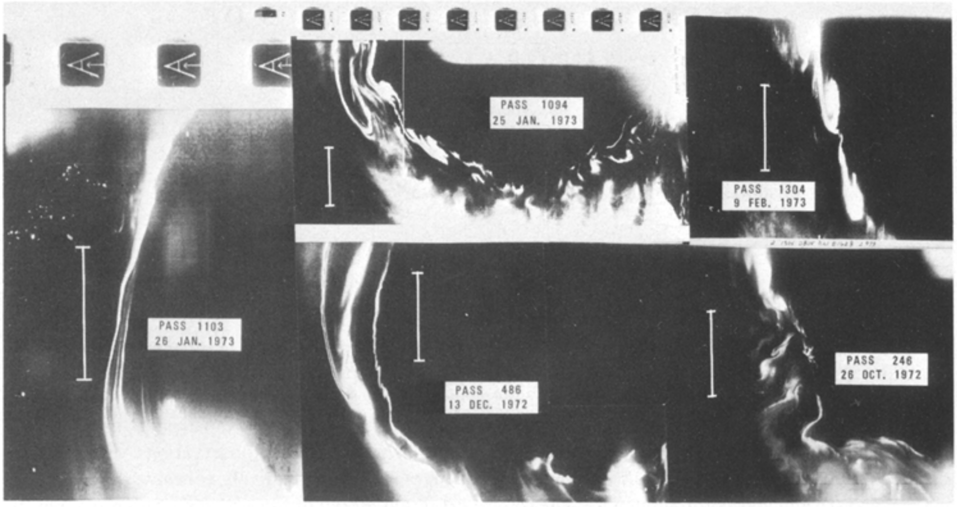


Fig. 1. Portions of DMSP images of discrete auroras in the northern hemisphere. The sun is approximately in the direction toward the top of each image. White bars indicate a distance of ~1000 km. Images from pass numbers 486, 1094 and 1103 show auroral arcs of great length. Images 246 and 1304 show spirals in discrete aurora; Image 1094 shows discrete aurora poleward of diffuse aurora extending from evening to morning.

In this review dealing with the observed characteristics of auroras, primary emphasis is given to two morphologically distinct types of auroras: discrete auroral arcs and pulsating aurora. These two types almost, but not quite, correspond to the discrete and diffuse aurora, since pulsating aurora is a subclass of the diffuse aurora, just as is the 'hydrogen' arc observed at the equatorward boundary in the evening sector. Another reason for not adopting the term 'diffuse' is that this term implies a diffuse character, whereas many of the forms one wishes to include in the classification are quite sharply defined. Such auroras appear diffuse to the visual observer or to the satellite scanner either because of their weakness or because the contrast between these forms and the background is often low.

As is shown in the companion paper by Swift (1978), the observed characteristics of the discrete aurora and the results of other measurements and chemical release experiments seem to fit together into a relatively cohesive picture suggesting that an understanding of the discrete aurora has been achieved. The same cannot be said for the pulsating aurora; its characteristics are complex and puzzling.

Most of the observations presented here, together with some minor interpretations, are summarized in Table I. Though it is not practical to discuss the characteristics of discrete auroral arcs and pulsating aurora simultaneously, there is value in summarizing the characteristics as in Table I, partly because that way the contrast between the two types of aurora is easily apparent. To a substantial degree, Table I forms a compact summary of Sections 2 and 3 of this paper. Broader reviews on the topic of auroras are given in the monographs by Omholt (1971) and

TABLE I

Summary of the important observed characteristics of two types of aurora, discrete auroral arcs and pulsating auroras

Definition of an Auroral Arc 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 range 100 eV to 100 keV.	*Definition of Pulsating Aurora* A pulsating aurora is one with maximum intensity never exceeding ~10 kR in 4278 Å and which undergoes at least one full cycle wherein there is first a rapid increase, then a rapid decrease in intensity. The pulsations are usually repetitive and often quasi-periodic.
Characteristics:	*Characteristics*:
1. Auroral arcs extend 100's to 1000's of kilometers in length, often parallel to the auroral oval; they occur singly or in multiple arrays.	1. Pulsating aurora occurs during the expansive and recovery phase of substorms and is most prevalent in the midnight and morning sectors, but also occurs in the evening sector.
2. The width of auroral arcs ranges from a minimum of 50 m (a few electron gyroradii) to a maximum of order 10 km. The boundaries are defined by steep gradients.	2. When both active, discrete auroras (arcs and bands) and pulsating aurora occur simultaneously on a given meridian, the pulsating aurora lies equatorward of the active aurora.
3. The lower border of an arc is sharp, in consequence of increasing atmospheric density with depth; the altitude is defined by the maximum energy of particles in the primary beam and is typically 80 km to 400 km, but mostly near 100 km.	3. Pulsating auroral forms are arcs, arc segments (arc-like but shorter) and patches of irregular shape. Widths of linear pulsating features are of order 1 to 10 km. Patches have horizontal scale sizes of order 10 to 100 km. Shapes repeat as forms quasi-periodically blink on and off.
4. The vertical extent to the diffuse upper border increases with the range of particle energy in the primary beam; it extends from a few km to more than 100 km.	4. Pulsating forms are usually immersed in a uniform or irregular background emission of intensity up to a few kilo-raleighs in N_2^+ 4278.
5. Arcs typically occur in multiple arrays. The spacing between arcs is probably random, but there may be preferred spacing near 2 km and perhaps near 5–10 km.	5. The altitude of the background emission is high (120–240 km); the altitude of the pulsating form is low (60–120 km).
6. Auroral arcs in the auroral ovals usually exhibit approximate conjugacy.	6. The height extent of pulsating aurora is sometimes, but not always, only a few kilometers.
7. Low-intensity arcs tend to have uniform boundaries and curvature. They often exhibit a fine-scale, field-aligned internal structure. The motion is less than that of bright arcs.	7. Some pulsating forms retain a fixed horizontal area during the pulse-on phase (stable pulsations). Others grow laterally during the pulse-on phase (streaming pulsations).
8. Brighter arcs often develop vortex streets (curls = rays) indicating strong, localized inward-directed **E**, also shown by differential shearing motions between closely-spaced multiple arcs. These shearing motions constitute $\mathbf{E}\times\mathbf{B}$ transport. $\mathbf{E}_\perp$ associated with an individual arc extends laterally over a region ~10 times the arc width. $\mathbf{E}_\perp$ is largest near the boundary of the recognizable arc.	8. Pulsating periods range from 0.3 s to 30 s.
9. Arcs may be submerged in a region of uniform background **E** which does not reverse direction across the axis of the arc.	9. A 3 ± 1 Hz modulation occurs in more than 50% of pulsating auroras in the midnight and morning sectors with modulation up to 20% of that of concurrent slower pulsations.

TABLE I – *continued*

10. There is upward electric current in the vicinity of bright arcs (intensity up to several times 10^{-6} amp m^{-2}).	10. Pulse shapes range from widely-spaced half-sine to closely-spaced square waves.
11. Convoluted arcs (bands) develop from uniform arcs when field-aligned currents perturb the direction of **B**, to produce new sheet beam configurations (folds and spirals). The ensuing apparent motions imply a changing magnetic field orientation and do not result from $\mathbf{E}\times\mathbf{B}$ drifts in an electrostatic field.	11. Pulsating auroras show east-west drift motions up to $\sim$1 km s^{-1} which may be $\mathbf{E}\times\mathbf{B}$ motion, but which are not always $\mathbf{E}\times\mathbf{B}$ motion.
12. $\mathbf{E}_\perp$ in the vicinity of auroral arcs *at ionospheric altitudes* typically does not exceed 100 mV m^{-1}.	12. Radically different pulsating behavior can occur on proximate flux tubes, but pulsating auroras *do not* exhibit shear motion phenomena.
13. But $\mathbf{E}_\perp$ well above auroral arcs (altitude >4000 km) can be $\geqslant$500 mV m^{-1}.	13. Exactly in-phase conjugate pulsations do occur, but other observations suggest that not all pulsations are conjugate. Out-of-phase conjugate pulsations have not been observed.
14. Bright arcs near time of breakup exhibit 10-Hz pulsing behavior (flickering).	14. Fluctuating electron fluxes depositing maximum of several ergs $(cm^2\,s\,sr)^{-1}$ in the energy range 50 eV to 100 keV occur above pulsating aurora. Outside the atmospheric backscatter cone electron fluxes are isotropic.
15. Upward oxygen ion fluxes occur in vicinity of auroral arcs.	15. Above pulsating aurora, increases in proton intensity correlate with increases in electron intensity. The proton spectrum softens as the electron spectrum hardens (greatest proton intensity near pitch angle 90°).
16. 'Inverted V' events in electron precipitation occur in vicinity of auroral arc structures.	16. Particle distributions above pulsating aurora tend toward isotropic or 'flat' rather than field-aligned.

Vallance Jones (1974); a monograph by Akasofu (1968) deals with the global substorm aspects of auroras and related phenomena.

2. Discrete Auroral Arcs

I depart from past practice by defining an auroral arc in a fashion suggested by Chamberlain (1961): "When we speak of the aurora we refer to the visual atmospheric radiation . . . To the physicist, however, a definition of a natural phenomenon, based on the characteristics of the human eyes seems most artificial. It would seem better to define the aurora with physical processes or prime causes in mind." There is danger in following this advice since it is easy to get into the realm of interpretation, interpretation that later is found to be wrong.

The reader will recognize the danger in the following definition of an auroral arc:

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 in the energy range $\sim$100 eV to $\sim$100 keV. The lower border is sharp, in consequence of increasing atmospheric density with depth; it has an altitude, typically 80 km 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 of order 10 km to more than 100 km.

This definition is based upon the assumption that the observed luminosity in auroral arcs is the result of particles impacting on the atmosphere. As far as is known, this assumption seems to hold for the nitrogen molecular emissions of the first negative system (3914, 4278 and 4709 Å), but it may not hold for the O I 5577 Å emission (Arnoldy and Lewis, 1977).

2.1. Auroral Arc Dimensions

A striking characteristic of auroral arcs is the great horizontal length relative to the width. As Figure 1 illustrates, arcs can exceed 1000 km in length. While it would seem an easy matter to observationally define the width, such is not the case.

Discrete arcs invariably have sufficient height extent, a few kilometers up to more than 100 km, to demonstrate that the alignment is along the direction of the local magnetic field. Consequently, an observation of the width with a remote sensing instrument, such as the eye, a photographic or photoelectric imaging device, or a spatially scanning photometer, must be made looking along the direction of the local magnetic field. Otherwise the height extent of the arc will cause the arc to appear wider than it actually is (see Figure 2). Only if the viewing point is contained between the two magnetically aligned planes bounding the arc can a proper measurement of arc width be made. Diameters of field-aligned cylindrical structures within discrete auroras can be measured viewing approximately at right angles to the magnetic field; using this method Booker *et al.* (1955) optically observed ray-like structures in active auroras to have diameters 100 m or less.

Störmer (1955) obtained a value of 7.4 km for the width of a homogeneous arc over Oslo; Harang and Omholt (1961) reported arc widths to 10 km and Kim and Volkman (1963) measured forty homogeneous arcs in the geographic zenith of Fort Churchill as having width 3.5 to 18.2 km and average 9.1 km. However, Elvey (1957) and Akasofu (1961), among others, reported observing active arcs with thickness of order 100 m. The extensive measurements of Maggs and Davis (1968) of 581 auroral structures appearing exactly in the magnetic zenith at College yielded widths from the instrumental cutoff at 70 m to 4.4 km and median thickness 230 m. Maggs and Davis argued away the discrepancy between their results and those reported by Kim and Volkman on the basis that the latter's observations in the geographic zenith prevented them from observing widths less than a few kilometers.

Maggs and Davis stated that their measured widths represented the distance between points where the luminosity was 2–5% of that in the center of the structure. However, we now know that the image orthicon television they used is capable of detecting a linear structure having rather low contrast with the background. Defining the percentage contrast as being 100 times the surface brightness

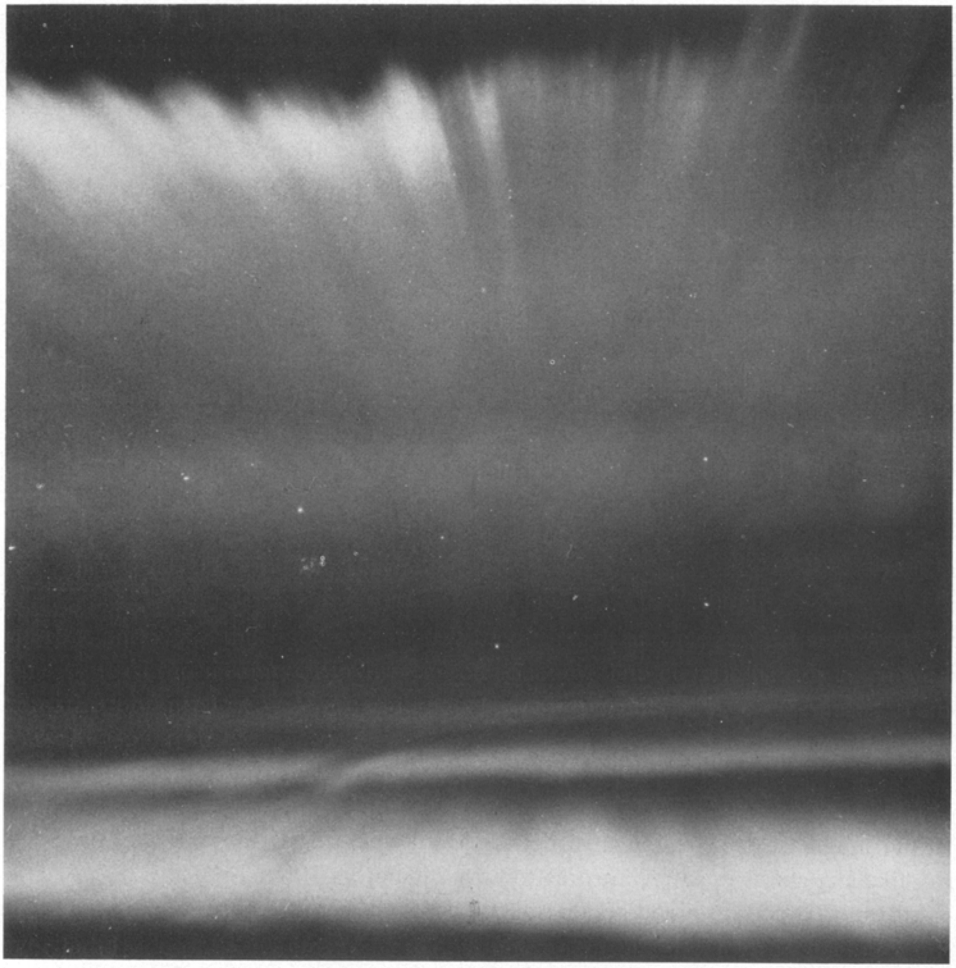


Fig. 2. Photograph by V. P. Hessler showing an array of parallel auroral arcs above College, Alaska. The second and third arcs from the bottom are near the magnetic zenith and therefore appear thinnest.

of the structure divided by the sum of the surface brightnesses of the structure and the background upon which it is superposed, the image orthicon TV can detect structures with contrast as low as 5 or 10%. Consequently, an arc with intensity only approximately one-twentieth of the intensity of the background (both wavelength integrated over the passband of the imager) can be detected. The measured width of such an arc would depend on scene contrast rather than the dynamic range of the instrument, as assumed by Maggs and Davis.

In those cases where there is extremely high contrast – the arc being one or two orders of magnitude brighter than the background – the dynamic range of the instrument could significantly affect the apparent width as would the profile of apparent surface brightness observed across the arc.

The results of Maggs and Davis should not be taken to imply that the auroral structures they measured were several times or even a decade or two brighter than the background in which these structures were immersed. However, the widths measured optically do appear to be realistic, since it is evident that the boundaries of auroral structures exhibit sufficiently steep gradients in luminosity to make the horizontal profile of surface brightness the determining parameter, rather than the instrumental dynamic range or the contrast response, in the measurement of width.

From the way discrete auroras stand out against the background, one is easily misled into thinking that the contrast is much greater than it actually is. The error leads to an apparent contradiction when viewing observations of precipitating electron flux obtained by rockets or satellites traversing the discrete aurora. The apparent contradiction probably disappears when account is taken of the fact that a discrete aurora can be visually or instrumentally distinguished from a background created by precipitating electron flux only 5 to 10% lower.

That agreement can pertain between ground-based imagery and rocket-borne measurement of electron flux is demonstrated by the results of Johnstone and Davis (1974) shown in Figure 3. The results presented there are unique in that both ground-based and rocket measurements were rather precisely on the same magnetic field lines, such observations being difficult to obtain. There are a number of papers in the literature reporting simultaneous optical and particle measurements that may appear to conflict with statements made here or elsewhere. In at least some cases, the apparent conflict is the product of low resolution in the optical measurement or in the inability to view in the direction of the local magnetic field.

The topic of the width of discrete arcs is worth close scutiny because of apparent differences in widths of auroras observed optically and the impression one obtains of the generally broader width of causative particle distribution above discrete auroras. Discrete auroral arcs can be very narrow – down to a few tens of meters – and, in fact, most active arcs are narrow, of order 100 m. Multiple arcs such as shown in Figure 2 are frequently observed. Such an array of arcs viewed away from the magnetic zenith (or the magnetic nadir, if viewing from above) can blend together to give the impression of a single broad arc. One could define the broad assemblage as being an arc with internal structure. However, the dynamical characteristics of the thin linear structures suggest that the name 'arc' be applied to the thinnest features observed and the name 'multiple arc' to an observed ensemble, a practice observed by Carl Störmer many years ago.

Visual observers have, over the years, had the impression that weak, homogeneous arcs tend to be broader than bright, rayed arcs. This impression may have arisen in part from failure to recognize that, often, the broad-appearing weak arcs were composed of several thin arcs, but the results of Maggs and Davis do show a strong trend toward thinner structures as the brightness increases: 68 IBC I or II structures averaged 740 m in width, 154 IBC II or III structures averaged 335 m and 16 IBC III or IV structures averaged 190 m (IBC refers to the International Brightness Coefficient; see, for example, Vallance-Jones, 1974).

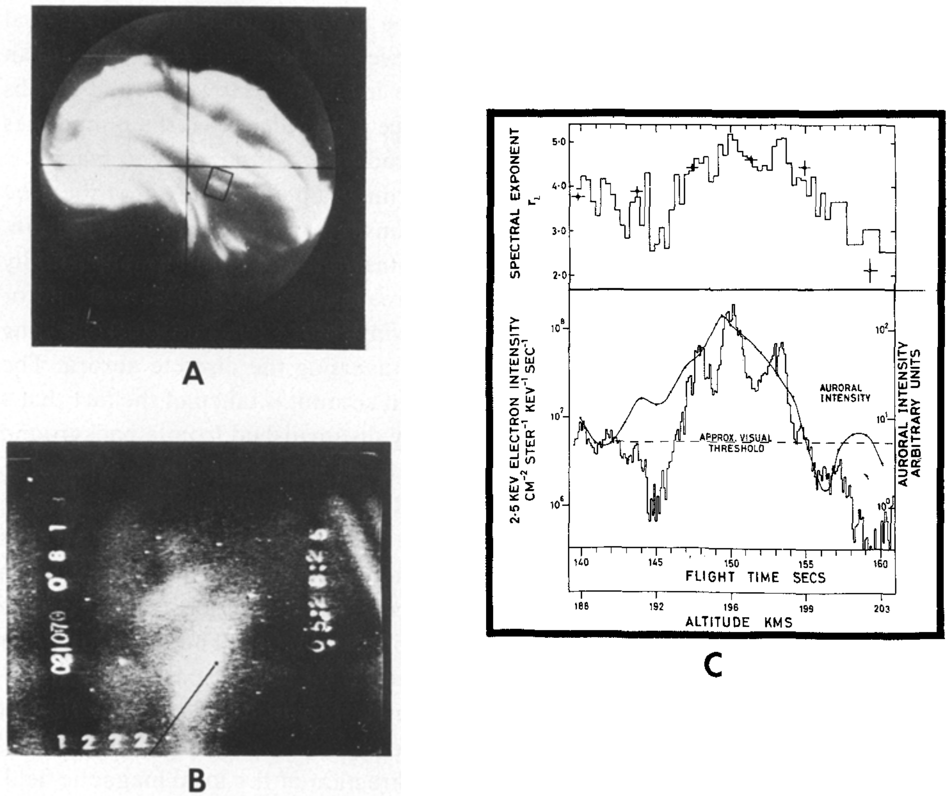


Fig. 3 A–C. (A) All-sky photograph showing the location of the television photograph (B). The small discrete aurora shown there was intersected by a rocket payload carrying particle detectors. The top panel of (C) shows the spectral exponent arising from fitting a power law to the electron spectrum. In the lower panel the trace of auroral intensity obtained from the television observations shows satisfactory agreement with the intensity of 2.5 keV electrons measured by the rocket. Compiled from figures presented by Johnstone and Davis (1974).

The altitudes of the lower borders of discrete auroral arcs tend to be in the vicinity of 100–110 km, indicating a maximum energy in the precipitated electron flux near ~8 keV; there are, however, substantial variations in the altitude of the lower borders over the range 80 km to several hundred kilometers. There are no observational or theoretical results to conflict with the view that if one knows any two of three parameters – (1) height-luminosity profile of nitrogen first negative emissions, (2) the atmospheric model or (3) the velocity distribution of precipitating particles – the third can be calculated using computations such as those of Rees (1963) or Berger *et al.* (1970). Results obtained using known electron beams launched from rockets (Hess *et al.*, 1971; Davis, 1974; Hallinan *et al.*, 1978; O'Neil *et al.*, 1978) are in accord with this view. Incidently, the observed diameters of artificial auroras produced by the electron beams are found to be small, from 30 m to perhaps 200 m, and thereby demonstrate that electron beams can be propagated hundreds to thousands of kilometers in the Earth's magnetic field without being spatially dispersed. On the other hand, Hallinan *et al.* (1978) have presented results indicating that conditions causing spatial dispersion do sometimes occur.

2.2. Spacing between arcs

The spacing between auroral arcs provides information on the scale sizes of phenomena leading to arc formation: see Section 3 of the companion paper by Swift (1978). Spacing between arcs observed with all-sky cameras was measured by Davis and Kimball (1962). Their results, relevant in the range 20 to 250 km, are presented in Figure 4a.

Additional measurements on arc spacing appear in Figure 4b. These represent the center-to-center spacing in the range 500 m to 25 km, the results being tabulated to the nearest 500 m; i.e., spacings between 500 m and 1499 m are recorded as 1 km, etc. The data used to compile Figure 4b were acquired on two nights in March 1968 by an image orthicon television camera equipped with a 50° field-of-view lens viewing vertically from a jet aircraft flying northward over Alaska. All measurements refer to active discrete auroras such as shown in parts C, D, E and F of Figure 15, to be discussed later.

Neither of the plots in Figure 4a and 4b show strong evidence of any preferred spacing between auroral arcs. Whereas the lack of spacings below 20 km in Figure 4a obviously is caused by low resolution of the technique used, the corresponding decrease in Figure 4b (fewer arcs spaced 1 km than 2 km apart) may be real. Plotted on Figure 4b is a Poisson distribution normalized to the data plot at spacing = 3 km. This curve approximately represents a random distribution of arc spacings. Comparison of the data plot and the curve is suggestive of some preference in the range 5–15 km. It may be that any departures from random spacing suggested by Figure 4a are simply artifacts of the measurements. Note that since center-to-center spacings are measured, a spacing of 2 km can pertain only to arcs less than 1 km in width. Whereas no attempt was made to measure simultaneously the width and spacing between arcs, cursory examination of the data indicate ratios of spacing-to-width between 5 and 10, at least where the spacing is less than approximately 5 km.

2.3. Motions and dynamical developments

The individual arcs of closely-spaced arrays, as in Figure 2, frequently show enough irregularity of structure to enable imaging systems to detect motions parallel to the length of the arc. Hallinan and Davis (1970) reported that when such motions occur, they are invariably opposite in direction across the center of the arc array and are in the sense shown in Figure 5. Speeds near 5 km s^{-1} are typical when rays are present, and speeds over 20 km s^{-1} have been observed. If interpreted as being caused by $\mathbf{E} \times \mathbf{B}$, these motions imply a transverse electric field associated with each arc and which is directed inward toward the arc. The apparent velocity increase toward the outer portions of an array implies that the field associated with each

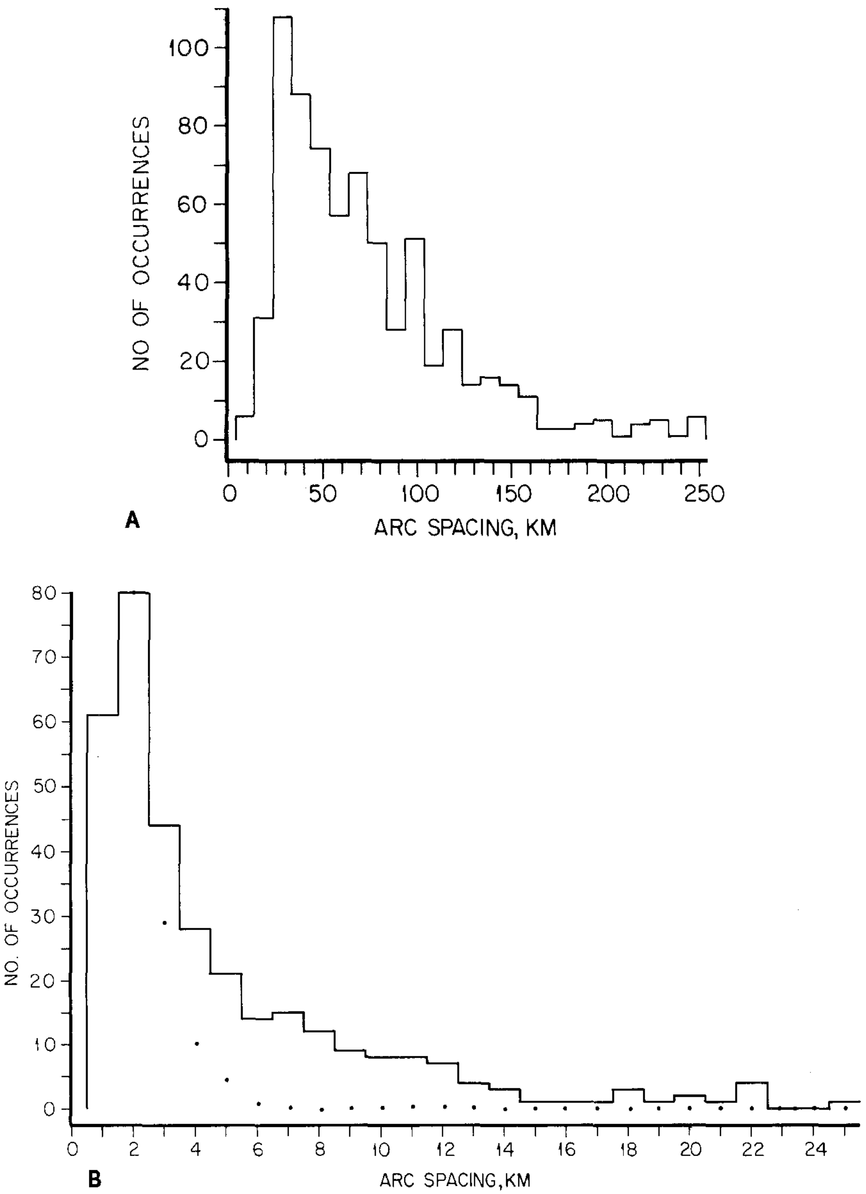


Fig. 4 A–B. (A) Spacing between discrete auroras reported by Davis and Kimball (1962) between geomagnetic latitudes 62° and 70° as obtained from all-sky camera observations. (B) Spacing between discrete auroral forms near the magnetic zenith and measured from television observations allowing resolution of several hundred meters. A Poisson distribution curve (solid dots) is fitted to the data with normalization at arc spacing 2 km.

individual arc extends well beyond the arc so that it adds to the fields of adjacent arcs. The required magnitude of the arc fields would be of order 100 mV m^{-1} and sometimes as large as 1000 mV m^{-1}.

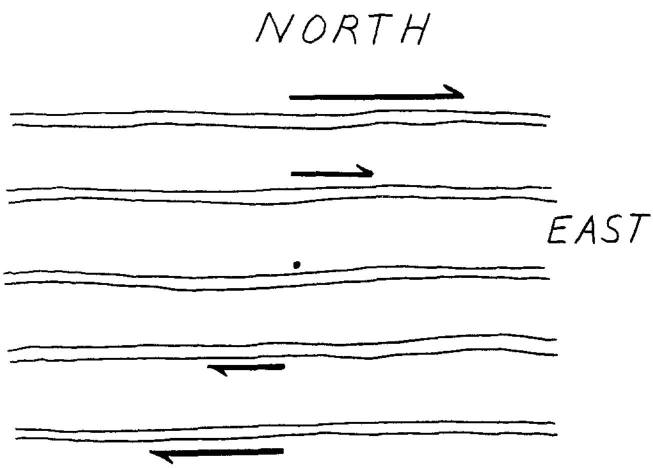


Fig. 5. Sketch drawing showing the relative motion between close-spaced auroral arcs as seen looking anti-parallel to the magnetic field. The lengths of the velocity vectors indicate higher speeds towards the outer boundaries of the arc array.

Also implying large-magnitude transverse electric fields in association with active auroras is the finding that auroral rays, at least in many instances, are vortex street structures (Hallinan, 1969; Hallinan and Davis, 1970).

Auroral rays seen from a point directly down the magnetic field line can be observed with high-speed imagers to develop in the manner shown on the right-hand side of Figure 6 into arrays of interconnected spots such as shown in Figure 7. Hallinan termed these structures 'curls' and showed that their development could be described by the dispersion relation for the Kelvin-Helmholtz instability for shear flow in an incompressible fluid. Using the fact that the space charge in a sheet is synonymous with vorticity, one obtains the transverse electric field necessary to provide the observed rate of curl development, the result being that fields of several hundred to 1000 mV m^{-1} are required. The curls are always observed to wind up in a direction requiring an inward-directed electric field, i.e., a negative space charge. The rotation sense is counterclockwise seen looking antiparallel to **B** in both north and south hemispheres.

The requirement for large-magnitude transverse electric fields to explain the rapid horizontal motions and development of curls was in conflict with ground-based, rocket-borne and low-altitude satellite observations showing that the required electric fields do not exist in the auroral ionosphere. Incoherent scatter radar observations (Banks *et al.*, 1974), direct probes (Aggson, 1969; Potter and Cahill, 1969; Mozer and Fahleson, 1970; Gurnett and Frank, 1973; Maynard *et al.*, 1973; Maynard *et al.*, 1977), and drifts of barium ion clouds (Wescott *et al.*, 1969), all indicate low-altitude electric fields rarely exceeding 100 mV m^{-1} and most indicate a reduction in the field magnitude toward the center of the aurora.

Contributing to the resolution of the conflicting evidence on the nature of the electric field associated with discrete auroras were results obtained from high-speed

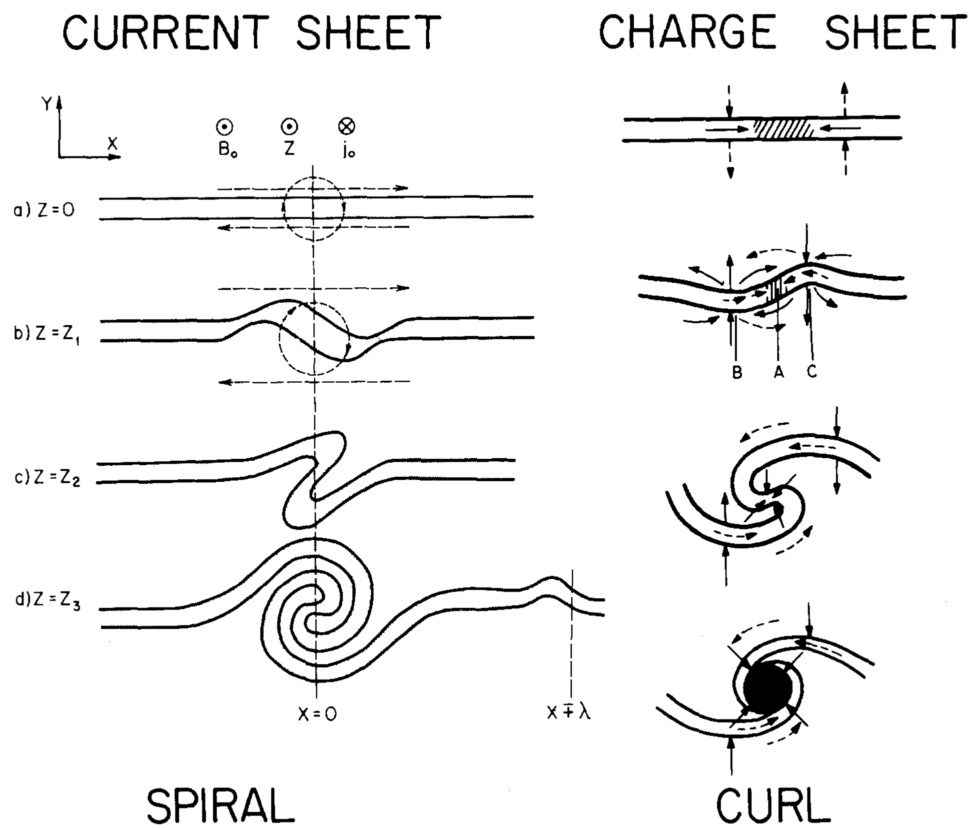


Fig. 6. Schematic illustration of the development of, at left, a spiral array and, at right, a curl. In the development of the spiral an initial local current enhancement ($x = 0$ in part a) results in a fold (part b) and further enhancement and distortion (part c). In part d a spiral has formed, and a new ripple is beginning to appear some distance (λ) to the right of the initial disturbance (after Hallinan, 1976). In the drawing at right the magnetic field also is directed out of the paper. The solid arrows indicate the direction of the perturbation electric field and the dashed arrows show the direction of the **E** × **B** electron drifts which cause the curl to form (after Hallinan and Davis, 1970).

barium plasmas injected onto magnetic field lines with the rocket-borne shaped-charge technique (Wescott *et al.*, 1974, 1975, 1976a). Just as the highly sensitive image orthicon and similar electronic imagers had allowed observation of the intricate details of the dynamical morphology of auroral forms, these devices have made it practical to observe at large distances the relatively weak emissions from the rocket-borne barium plasmas. In applying this method, barium ions are ejected upward along the direction of the magnetic field at speeds in excess of $10\ \mathrm{km\ s^{-1}}$ from an altitude above most of the atmosphere, typically ≥450 km. With shaped-charge assemblies weighing near 20 kg and containing a liner of barium weighing near 1 kg, existing imaging systems allow tracking of the resultant barium jets beyond altitude 20 000 km and with a temporal resolution of several seconds.

An early experiment at low altitude (Westcott *et al.*, 1974) made observable an entire magnetic field line and helped demonstrate that even here the field line was

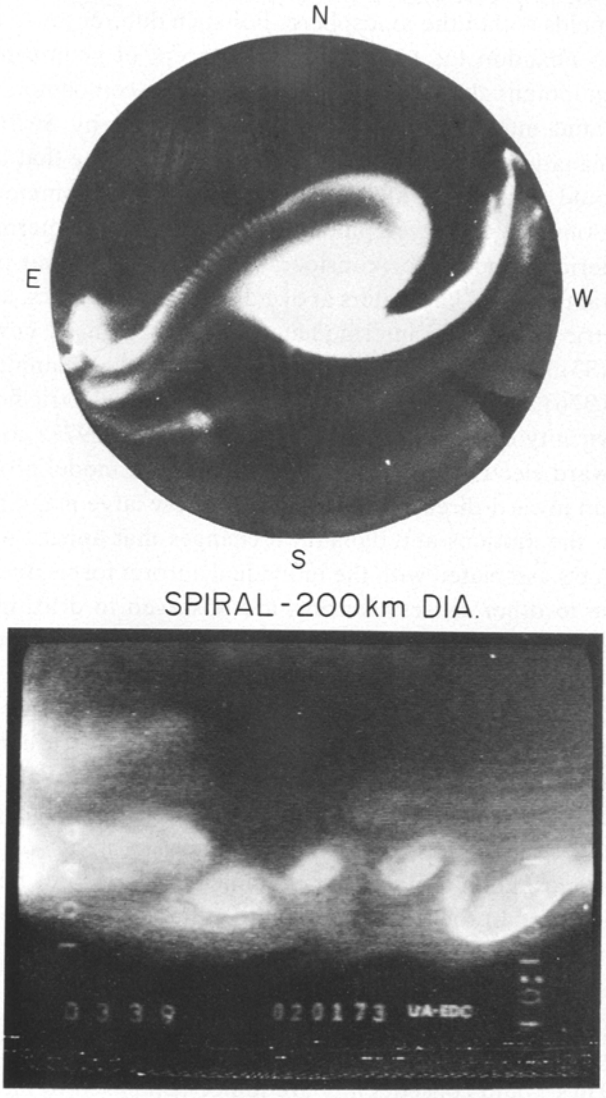


Fig. 7. *Top*: All-sky photograph showing both spirals and the smaller-scale ray structure caused by curls, as shown in the television photograph at bottom viewing anti-parallel to B. The all-sky photograph was taken at Fort Yukon, Alaska on 24 March, 1968: the TV photograph was taken at College on 1 February, 1973.

not an equipotential nor was its configuration that thought to exist on the basis of existing models of the geomagnetic field. Later experiments at the auroral zone (Wescott *et al.*, 1975, 1976a, b) showed radically different behavior along magnetic field lines. This behavior could be explained by the existence of very large electric fields at locations several thousand kilometers above the ionosphere and much smaller electric fields within the ionosphere. For such differences to be accepted, it was necessary to abandon the long-cherished concept of geomagnetic field lines always being equipotentials. As discussed fully in the companion paper, the V-shock equipotential model for an auroral arc proposed by Swift *et al.* (1976) provided an explanation of the apparent conflict by predicting that high transverse electric fields would exist at high altitude (several thousand kilometers) to cause the fast auroral motions and the development of curls. This model permits the electric field at ionospheric altitude to be considerably smaller than that occurring at an altitude of several thousand kilometers above discrete auroral arcs, and it allows for an upward electric field in the intermediate altitude region. A new high-altitude polar satellite (S3-3) obtaining observations of upward streaming positive ions (Shelley *et al.*, 1976) and very large and highly structured electric fields ($\sim\frac{1}{2}$V m^{-1}) in the general vicinity of altitude 8000 km (Mozer *et al.*, 1977) confirm the existence of the upward electric field and lend support to the model proposed by Swift *et al.* involving an inward-directed electric field of very large magnitude.

In addition to the motions and dynamical changes that appear to be caused by space charge effects associated with the individual auroral forms, there are motions and changes due to other causes. Auroras are observed to drift, mainly east and west, with speed and direction approximating the drift of ionization such as is observed by incoherent scatter radar or in the transverse motion of barium ion clouds injected at ionospheric altitude. This drift is generally attributed to magnetospheric convection (Axford, 1969). The magnetospheric convection can be inferred by observing the low-speed (up to 2000 m s^{-1}) drifts of auroral forms; the results are similar to that obtained by examining the concurrent magnetic horizontal disturbance vectors (Davis, 1971). Direct measurements of the horizontal electric field at ionospheric altitude can be difficult to interpret because the field there can be composed of the highly-structured field of the arcs superposed on the relatively uniform convection electric field.

Also, to the extent that the aurora occurs in the fixed auroral oval pattern, there is apparent motion owing to the rotation of the ground-based observer. The resulting westward, southward (in evening) and northward (in morning) motions do not exceed 200 m s^{-1} and consequently are minor compared to all other motions.

Contrasting with the always counterclockwise (viewing anti-parallel to **B**) development of the small-scale vortexes called curls are clockwise folding motions and formations of large vortex structures (Davis and Hallinan, 1976; Hallinan, 1976a). To distinguish them from curls, the larger clockwise vortices are called spirals. Examples appear in Figures 1, 3 and 7. At minimum, spirals are an order of magnitude larger than curls, the largest so far observed being 1300 km in diameter (Anger and Lui, 1973). Hallinan (1976b) has shown that spirals are created from arcs by the effects of upward current (downward-moving electrons). As shown in Figure 6, the magnetic field of the upward current sheet associated with the arc is transverse and oppositely directed on the two sides of the arc. It adds to the ambient field to yield a new field with direction slightly different from that of the original field. If the current in the sheet is sufficiently intense and if the length of the sheet along **B** is great enough, a small perturbation will lead to the formation of a vortex as shown in Figure 7. Hallinan has shown that the equilibrium state of a Birkeland current sheet is one in which one end of the sheet is distorted into a vortex street. On auroral zone magnetic field lines the threshold current density to cause a spiral to form is approximately 10^{-5} amp m^{-2}. The sketches in Figure 8 help illustrate the differences between the curl and spiral vortex configurations in the discrete aurora. Whereas the curl is the result of an absolute instability, the spiral is a convective equilibrium configuration. Increase of current in the sheet causes the spiral to further wind up; decrease of current causes it to unwind. Both winding up and unwinding is observed in the aurora.

It is significant that curls and spirals can occur simultaneously within a discrete arc, as shown in Figure 6. In fact, Hallinan (1976b) uses this simultaneity to suggest

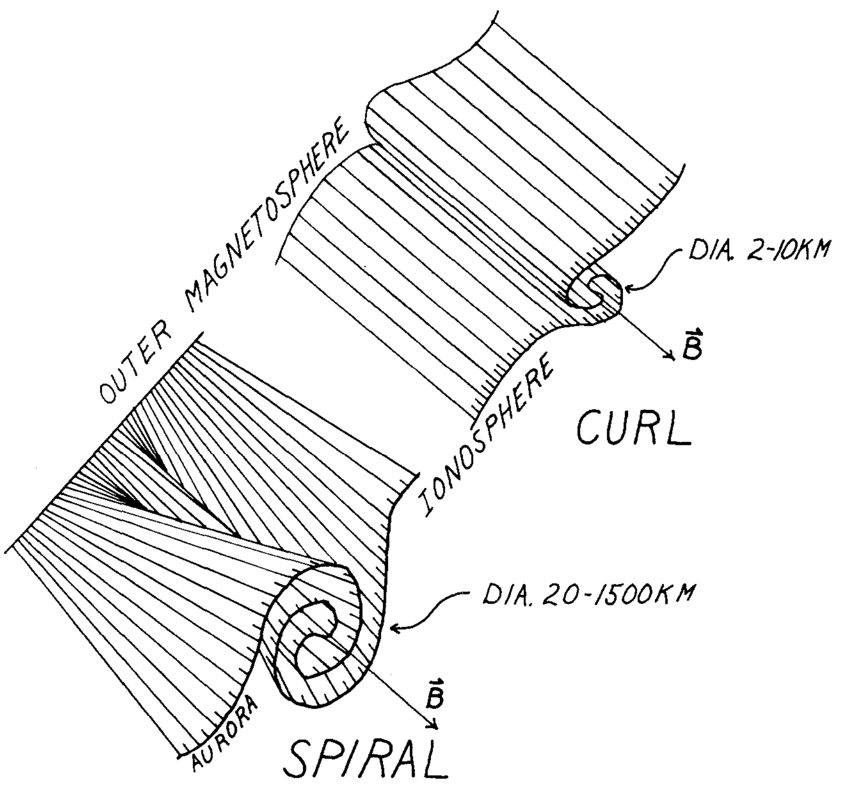


Fig. 8. Sketch drawing showing the convective nature of the spiral and the absolute nature of the curl, the differences in scale size between the two developments and the opposite senses of rotation. Although the magnetic field lines are drawn in as being straight in the sketch of the spiral at left, in actuality these field lines will be curved and helix-like.

that folding occurs at a scale size where there is conflict between the counterclockwise shear attributed to the charge sheet and the clockwise shear of the current sheet. At these scale sizes the wavelength normally leading to the formation of spirals is suppressed, but wavelengths creating folding are not. In viewing the discrete aurora, one frequently sees the development of sinusoidal distortions to arcs followed by suppression, so it is obvious that there often exists a delicate balance between suppression and growth.

Extensive observations of morphological changes in discrete aurora also have been obtained by Oguti (1974, 1975) with high-speed imaging devices at Syowa Station, Antarctica. His descriptions of the initial development of convolutions in discrete arcs differ from those of Hallinan and Davis, cited previously, in that Oguti gives greater emphasis to what he terms splitting. Splitting and other developments identified by Oguti are schematically illustrated in Figure 9, and an actual example of splitting is shown in Figure 10.

In seeking to explain why Oguti has recognized splitting as an important initial step in the development of convoluted auroral forms whereas our Alaska group has not, one notices that for much of its detailed work the Alaska group has used small fields of view (12°×16°), whereas Oguti used primarily a 60° field of view. This

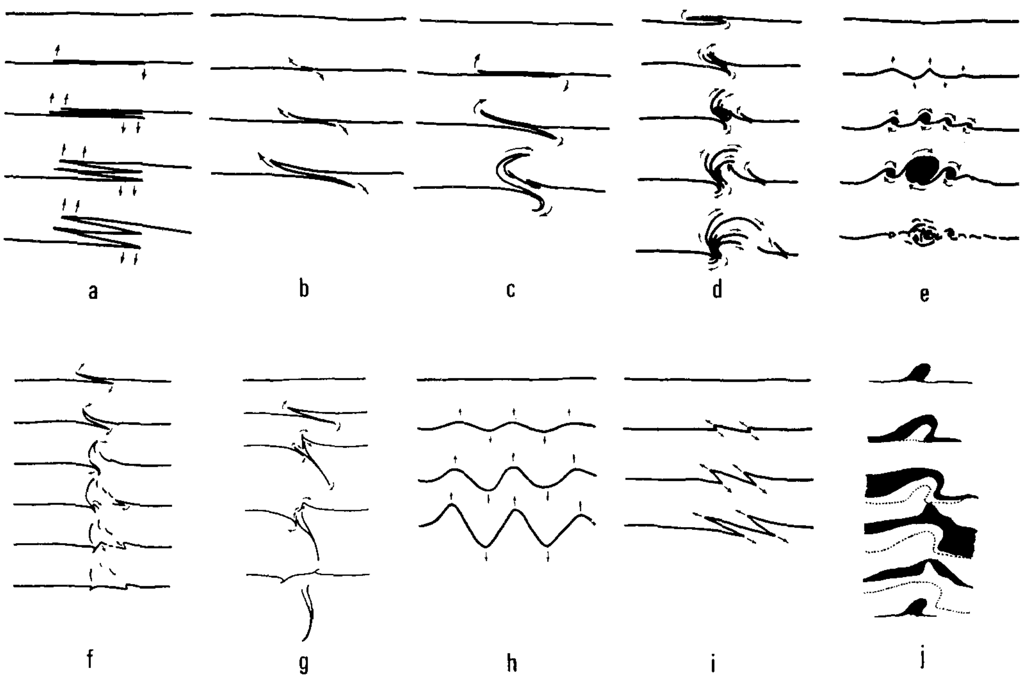


Fig. 9. Schematic illustrations of elementary deformations. (a) simple splitting, (b) protrusive splitting, (c) folding over, (d) leading rotation, (e) trailing rotation, (f) sheet to sheet deformation (disruption and reconnection), (g) sheet detachment, (h) simple meandering, (i) shear folding, (j) quasi-periodic sequential switching (after Oguti, 1975).

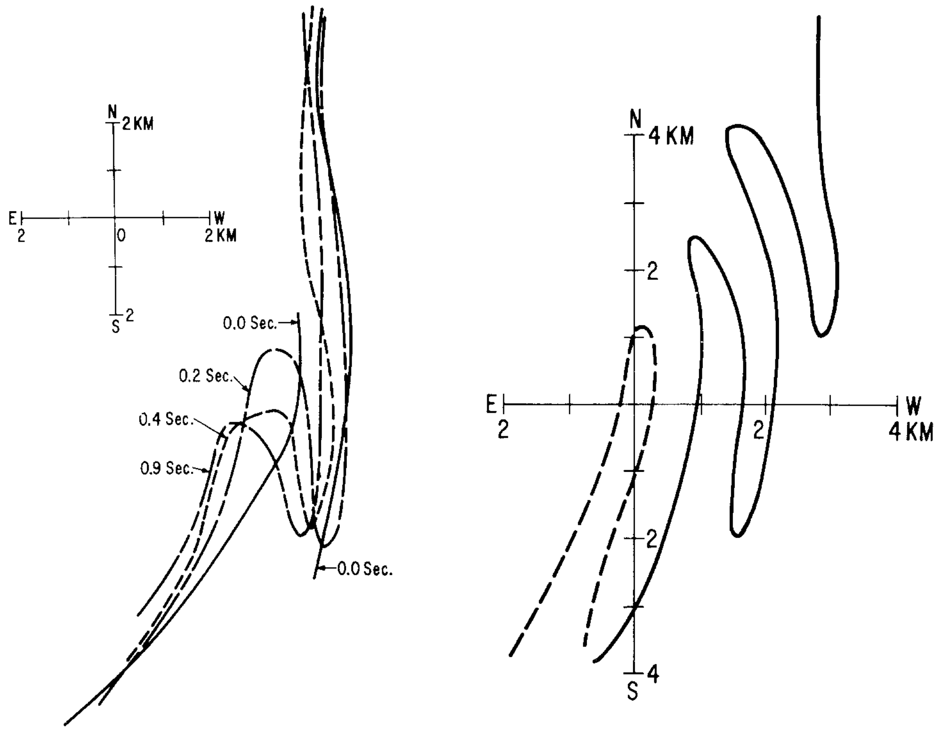


Fig. 10. An example of a splitting deformation observed with a television system viewing the magnetic zenith at Fort Churchill. A few seconds after the splitting occurred, the arc developed the folding pattern shown at right (after Davis, 1965).

difference, in itself, should not affect the results obtained, except that it is obvious that the Alaska group has tended to emphasize observations looking nearly parallel to the magnetic field and to largely ignore those taken at larger aspect angle. There can be no question that the changing aspect angle created by the motion of an auroral form relative to the observer's magnetic zenith creates apparent but unreal deformation. Nevertheless the splitting described by Oguti does occur. Since the centerline of an auroral arc does appear to be a boundary across which opposing shear takes place, it may be that splitting is another manifestation of shear processes wherein the motion is nearly all parallel to the centerline of the arc.

Two conceptually different types of auroral motion have been discussed so far. One is the movement of entire flux tubes as will occur under $\mathbf{E} \times \mathbf{B}$ motion when the parallel electric field is zero. The other type is motion resulting from tipping of flux tubes when field-aligned current alters the orientation of the flux tube. Yet another type of apparent auroral motion, one that could be called successive dumping, occurs in displays of active, discrete aurora, especially near the time of breakup (Kelley *et al.*, 1971; Davis, 1971). In watching this type of apparent motion, the observer is readily convinced that the observed auroral precipitation is coming from one flux tube at one time and a different nearby flux tube shortly later. Sometimes noticeable during poleward surges are the repeated formations of a new arc just northward of a pre-existing arc that disappears seconds or tens of seconds later. In such instances there is often added complexity caused by contra-streaming longitudinal motion. Consequently, it is difficult in such instances to sort out and adequately describe the various components of the apparent motion. However, it is easy to interpret 'successive dumping' by use of the V-shock model of Swift *et al.* (1976) by associating the successive appearance of precipitation in a new flux tube as the result of the formation of a new V-shock.

Also relevant to the successive dumping type of apparent motion is the comment of Hallinan (1976b) that it may be possible for field-aligned current associated with fold or spiral formation to change so rapidly that the shape of the sheet is unable to evolve so as to retain an equilibrium condition. The development of new V-shocks and the associated successive dumping might be a consequence of such rapid change.

One other type of quasi-motion involving an apparent 10-Hz variation occurs in bright, active auroras, especially near breakup. This phenomenon, called flickering, can sometimes be detected visually and is readily observed in television recordings (Beach *et al.*, 1968) and by high-frequency radar (Sofko and Kavadas, 1969); it also has been detected in rocket-borne measurements of electron precipitation (Evans, 1967). In television recordings flickering is seen to affect broad regions of order 10 km across. It appears to involve not only a periodic variation in auroral intensity, but also a rather jerky quivering of the flux tubes containing the auroral precipitation. It is not obvious whether flickering is a recorded phenomenon of little consequence or an important component of the breakup process. Positive correlation between riometer absorption and flickering (Beach *et al.*, 1968) does indicate association with relatively high-energy electron precipitation.

2.4. Conjugacy of Discrete Auroras

With awareness that field-aligned currents modify the orientation of flux tubes above discrete auroral arcs, it is somewhat easier than in the past to understand observations of the degree of auroral conjugacy. Since the average orientation of an auroral zone magnetic field line can change by as much as one-half degree during the formation of an auroral spiral, one readily sees why experimental efforts to make conjugate measurements at different altitudes on auroral zone field lines can only lead to failure or can, at least, yield indeterminant results.

Figure 11 provides a brief summary of many of the results on hemispherical auroral conjugacy described in a series of related papers (Belon *et al.*, 1969; Stenback-Nielsen *et al.*, 1972; Stenbaek-Nielsen *et al.*, 1973). The diagram illustrates the high degree of conjugacy of quiet auroras of diffuse nature and a lessening degree of conjugacy of the discrete forms ranging to the extreme (Part F) of total failure of conjugacy. Observed displacements in conjugacy by several hundred kilometers (Stenbaek-Nielsen *et al.*, 1972) could be caused by differences in the growth of field-aligned currents in the two hemispheres. That idea does not help explain the

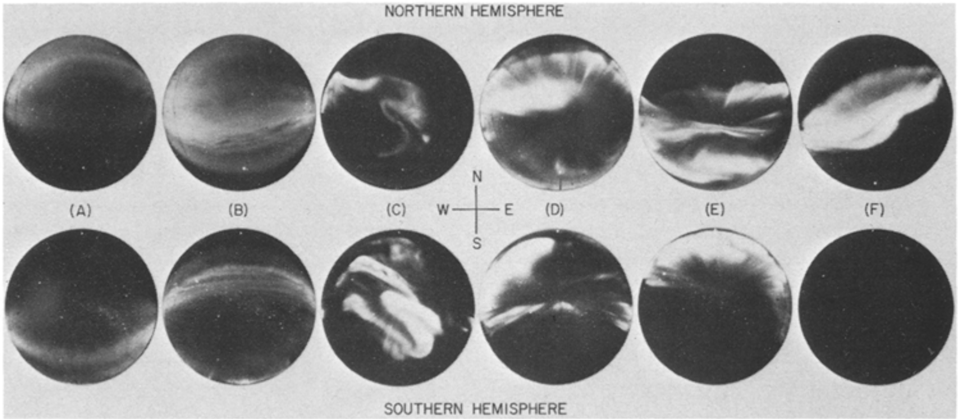


Fig. 11. Representative examples of conjugate all-sky photographs from March 1968 aircraft flights. Photograph pairs (A) to (F) represent increasing geomagnetic latitudes. Note similarities in pairs (A), (B) and (C) and the complete breakdown of auroral conjugacy in pair (F) (after Belon *et al.*, 1969).

observed tendency for equatorward and eastward displacement of the active, discrete auroras of the southern hemisphere relative to those of the northern.

That highly-conjugate, if displaced, active auroras do occur does imply that such auroras are on closed field lines – at least to the extent that there is inter-hemispherical communication along them. Similarly, observations of relative intensity of conjugate auroras (Stenbaek-Nielsen *et al.*, 1973) indicate that a substantial fraction of auroral particles producing active auroras are at least quasi-trapped, also indicating a degree of field line closure.

2.5. Interpretation of observations

The V-shock model of an auroral arc proposed by Swift *et al.* (1976) was remarkably successful in making sense of observations that previously seemed mutually contradictory. Further, the model's prediction of upward electric fields above auroral arcs and very large transverse electric fields at high altitude were soon substantiated by the S3-3 satellite observations reported by Shelley *et al.* (1976) and Mozer *et al.* (1977).

Still, there is a problem. One needs to associate the V-shock model with an individual auroral arc to explain the electric fields associated with the arc. But, to explain the energy spectra in inverted-V structures (Frank and Ackerson, 1971), it also is desirable to associate the V-shock model with the inverted-V structure, which may be of order 10 times the width of individual auroral arcs.

One way out of the quandary is suggested by Swift (1978), but another is suggested by the sketch drawings shown in Figure 12. There the V-shock model is associated with an individual auroral arc, as shown on the left side of the figure. Since close-spaced auroral arcs are observed, closely-spaced V-shock structures are implied, as shown at center of Figure 12 and even overlapping ones as shown at

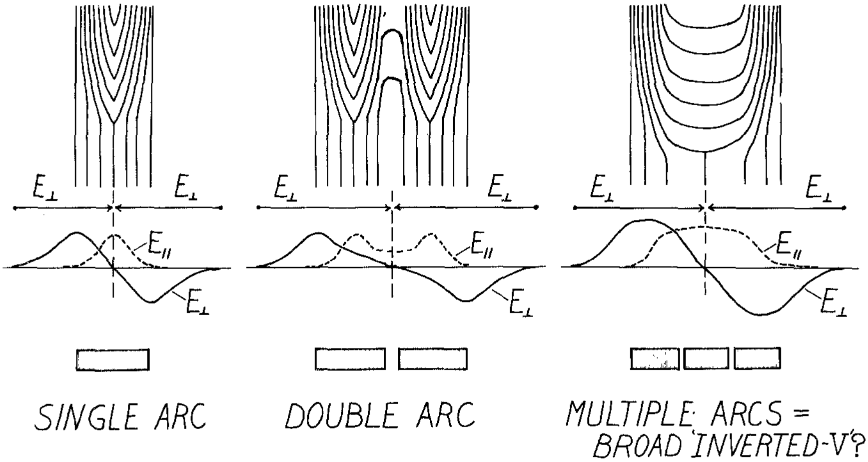


Fig. 12. At left, the V-shock model associated with a single aurora arc. The electric fields $E_\perp$ and $E_\parallel$ sketched in represent the fields that should appear well above the aurora and in the V-shock structure. At center, two V-shocks are placed side by side, and, at right, three identical V-shocks are overlapped. Minor inconsistencies between the plots of electric field and the equipotential distributions are due to omission in the sketches of equipotentials outside the arcs.

right. These three sketches illustrate that the basic configuration of the transverse electric field is unchanged, and the parallel electric field behaves similarly, if adjacent or overlapping V-shock structures are permitted. Thus, there is no conflict between assigning the V-shock model to a thin auroral arc and also expecting the concept to explain the much broader and structured inverted-V events.

Note that the transverse electric fields shown in Figure 12 appear not in the ionosphere but rather several thousand kilometers higher, up within the V-shocks. These structured electric fields only partially map down to the ionosphere where measurements should show a superposition of the convection and the V-shock structure electric fields. Since the meridional convection electric field need not reverse itself across the axis of the V-shock ensemble, the poleward-directed convection field in the evening sector should add to the poleward electric field existing in the equatorward portion of the V-shock. Thus the largest magnitude of meridional (poleward-directed) electric field in the evening sector should appear near the equatorward boundary of the discrete aurora. Similarly, when the convection field is directed equatorward, as is often true after midnight, the largest meridional electric field should be on the poleward boundary of discrete aurora and be directed equatorward, unless the convection field near the poleward boundary of the aurora is primarily directed east-west.

The addition of the convection and arc-associated electric fields to produce a stronger poleward-directed field near the equatorward boundary of an arc system in the evening sector could explain observations, such as by Evans *et al.* (1977), of the electro jet being strongest outside or near the equatorward boundary of the discrete aurora.

Since the upward electric field is presumably greatest toward the center of an auroral arc (see Figure 12), it would seem that the largest upward current should also be in the center of the arc. While some observations support this association, others indicate upward current near the boundaries of the auroral arcs and even more complex patterns (Anderson, 1977). In those cases where the largest upward current is located near the boundary of the aurora, the current evidently carried by low-energy electrons (of order 100 eV) and the visible aurora itself is associated with a flux of higher-energy electrons, as in Figure 13. Anderson notes that even in those cases where the upward current is concentrated near the edges of the aurora, the current is still centered on the arc.

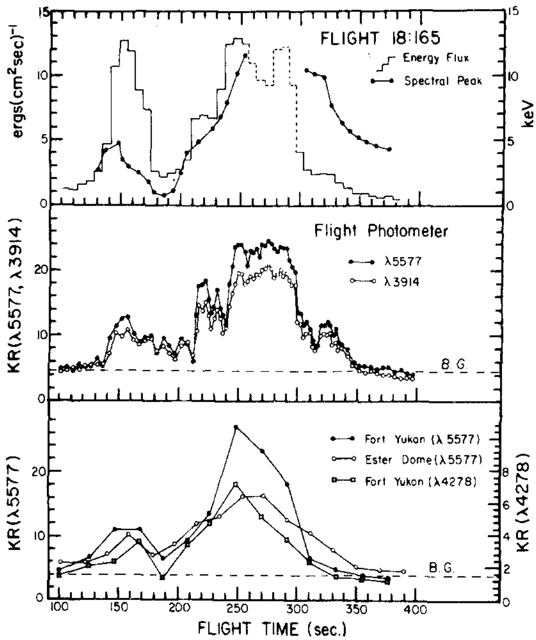
Very likely, many of the apparently contradictory results obtained in trying to associate particle and field measurements with optically determined auroral forms are the consequence of the difficulty in locating and defining the width of the auroral form. Time and again one sees an auroral arc sweep through the magnetic zenith only to realize that the arc is actually two or more closely-spaced arcs. Even so, it is perhaps not obvious that rocket and satellite data on particle precipitation and field-aligned currents contain the spatial detail that the ground-based observations seem to require.

3. Pulsating Aurora

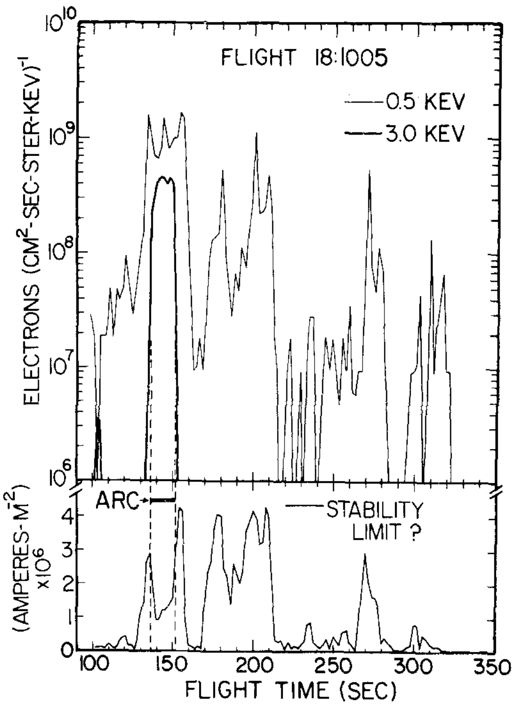
3.1. General characteristics

Cursory examination of Table I reveals the remarkable differences between arc-like discrete aurora and pulsating aurora. The pulsating aurora lacks the high intensity, rapid motion and shearing phenomena that seem to be related to electric fields and field-aligned currents associated with active discrete aurora. Here, the term pulsating is used in the restricted sense implied by the International Auroral Atlas (*International Union of Geodesy and Geophysics*, 1963) which treats pulsating as a subclass of pulsing aurora. That broader class of quasi-periodic auroral behavior includes variations involving bright forms and perhaps rapid oscillating motions. While pulsating aurora has distinctive characteristics, the total array of the observed characteristics does not, at present, fit well with any proposed model of particle precipitation and excitation. Consequently, it is difficult to provide a meaningful and cohesive description of the phenomenon. The pulsating aurora constitutes an important part of the overall display since it, together with the diffuse background emission upon which it is superposed, represents a substantial fraction of the overall energy input to the ionosphere during an auroral substorm.

The principal characteristic of pulsating aurora noted by photometric observation is the quasi-periodic intensity fluctuation with period 0.1 s to several tens of seconds with greatest power spectral density in the range 2 to 10 s (Campbell and Rees, 1961; Iyengar and Shepherd, 1961; Paulson and Shepherd, 1966a, b; Johansen and Omholt, 1966; Omholt and Pettersen, 1967; Shepherd and Pemberton, 1968; and Pemberton and Shepherd, 1975). The photometric observations also

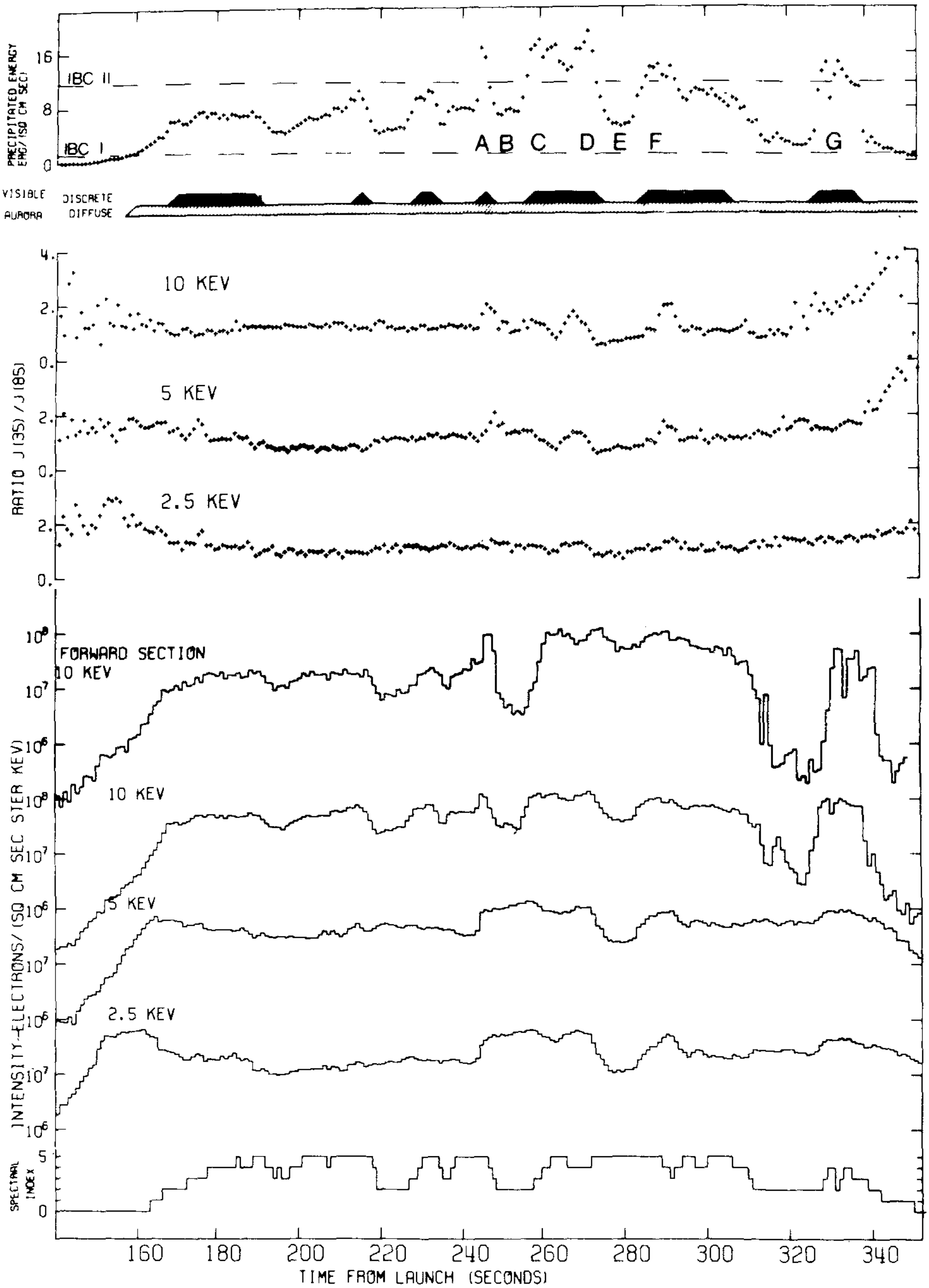


A



C

Fig. 13.A–C. (A) Results published by Arnoldy and Lewis (1977) showing a spectral peak in electron fluxes associated with a broad region of aurora and the related emissions observed on the rocket and from the ground. (B) Results published by Boyd and Davis (1977) showing a broad region of electron precipitation in which auroral arcs are identified and are seen to be associated with increases in flux,



B

spectral hardness and tendency toward greater field alignment. (C) Top panel, directional intensities at 0.5 keV and 3 keV. Bottom panel, measured field-aligned current and the location of an auroral arc measured at 5577 Å. Note the association of the field-aligned current with the defined boundaries of the arc. After Arnoldy (1977).

show that pulsating aurora never exceeds a brightness greater than 10 kR in 4278 Å N_2^+ first negative group. Thus, pulsating aurora is generally much weaker than active discrete aurora.

Television imaging observations by Cresswell and Davis (1966), Scourfield (1970), Scourfield and Parsons (1971), Oguti (1975), and Royrvik (1976) have yielded additional information on the complex shape and temporal variations of pulsating auroras leading to a new view of the essential characteristics of pulsating aurora. According to Royrvik and Davis (1977) the distinguishing characteristic is the rapid increase and decrease in intensity rather than the quasi-periodic behavior. However, they present examples of pulsations ranging from widely spaced half-sine shapes to closely spaced square-wave shapes. They also report that more than 50% of pulsating auroras exhibit an additional 3 ± 1 Hz modulation superposed on the slower pulsations.

3.2. Global distribution

While it has been long known that pulsating aurora is prevalent in the recovery phase of the substorm, especially in the morning sector, Royrvik (1976) and Royrvik and Davis (1977) have recently utilized a combination of all-sky television and DMSP satellite images to show a wider distribution. They found that some pulsating occurs in the evening sector near the equatorward edge of westward-traveling surges near the time of onset of the substorm expansive phase. The summary diagram in Figure 14 shows the extensive distribution of pulsating aurora during the later phase of moderate to large substorms.

3.3. Small-scale morphology

In contrast to discrete auroras, which always are basically linear in form, pulsating auroras are of various shapes. The weak, infrequent pulsations in the evening sector early in the substorm involve everywhere-synchronous intensity variations of stable arcs 1 to 10 km in width. Shorter arc-like segments and patches of irregular shapes and up to sizes of order 100 km also occur in the midnight and morning sectors. In addition to pulsations involving the switching on and switching off of regions of fixed area, there is a type described by Scourfield and Parsons (1971) which grows spatially. Royrvik (1976) termed this phenomenon streaming; an example is shown in Figure 15. Streaming usually involves outward growth from an irregular core area followed by contraction or disappearance as the pulse decays.

Whereas radically different pulsating behaviors are observed within adjacent auroras, or during a sequence of pulsations within one aurora, pulsating auroras contrast greatly with discrete auroras by showing only slow drift motions and little or no differential motion (shearing) between forms. Particularly in the morning sector, the prevalent drift is eastward at speeds of order 1 km s^{-1}. This appears to be an $\mathbf{E} \times \mathbf{B}$ convection drift, but we have noted at times that the eastward auroral drift is slower than that of eastward moving barium ion clouds, which presumably move at the speed dictated by $\mathbf{E} \times \mathbf{B}/B^2$. Swift and Gurnett (1973) also found lower

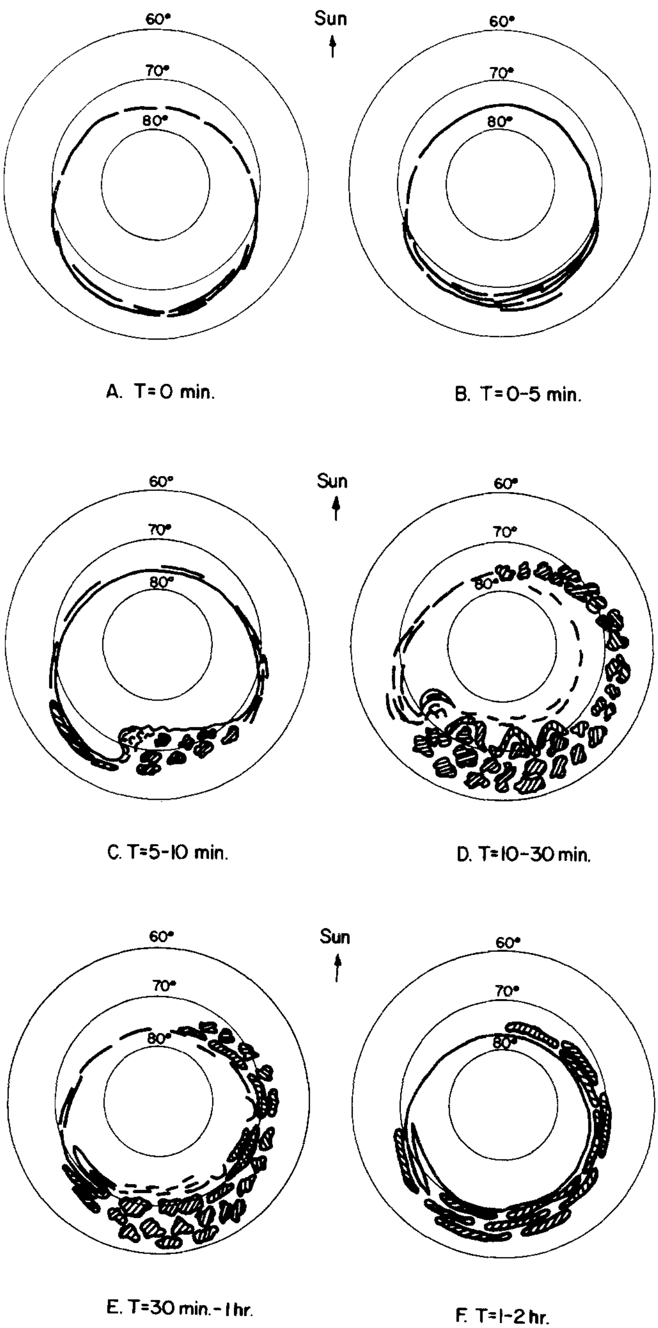


Fig. 14. Schematic diagram illustrating the development of an auroral substorm and emphasizing the distribution of pulsating auroras during the substorm. The pulsating forms are indicated by hatched regions superposed on a similar diagram presented by S.-I. Akasofu (after Royrvik and Davis, 1977).

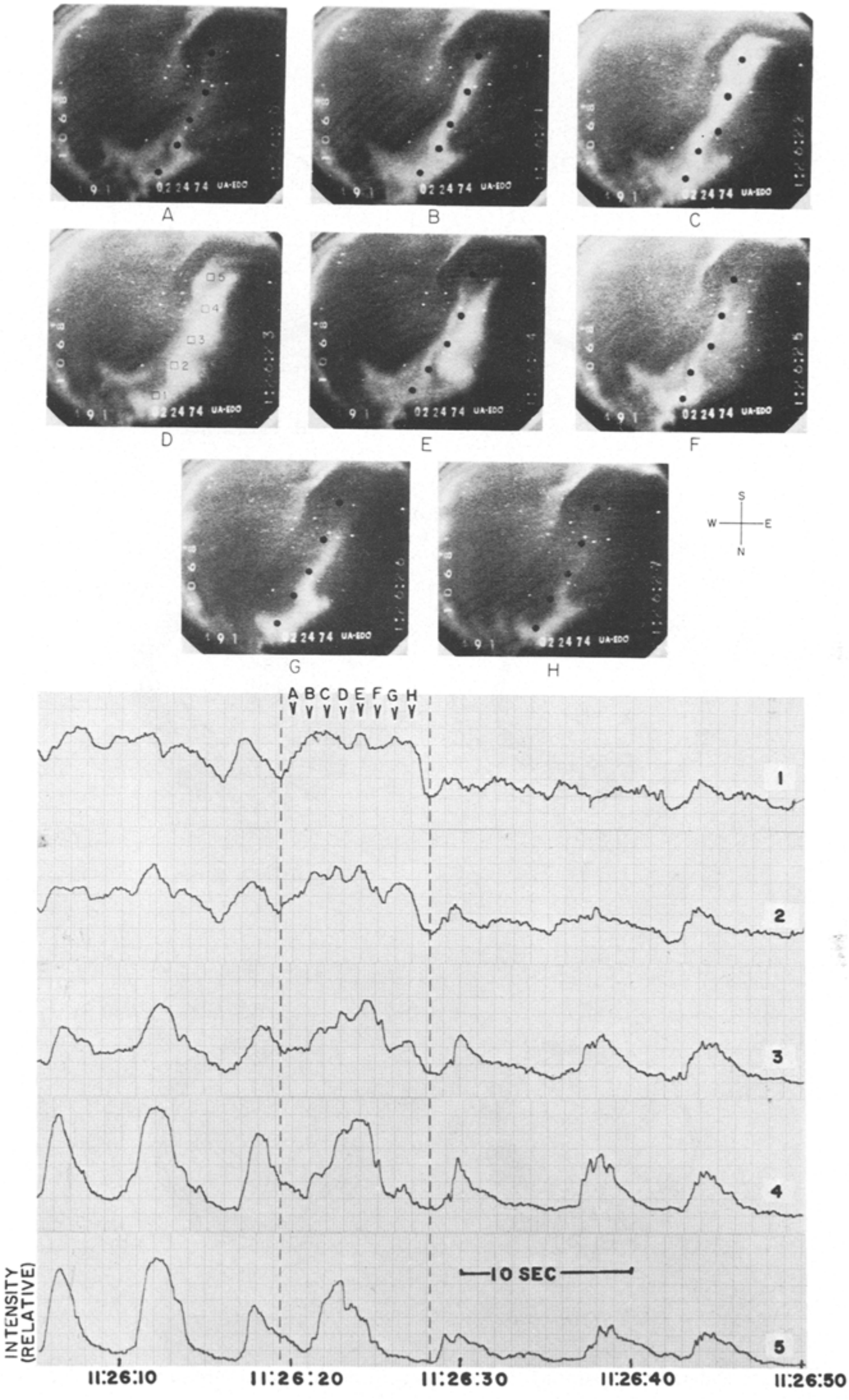


Fig. 15. All-sky television data from 24 February, 1974 showing the variation of intensity at points labeled 1–5 on a pulsating patch showing the streaming (outward growth) behavior (after Royrvik and Davis, 1977).

eastward drift speed in pulsating aurora than would be expected from concurrent observation of the low-altitude convection field. Scourfield and Parsons (1971) noted that the majority of pulsations of the streaming type in the post-midnight sector moved westward rather than eastward. Though generally eastward, motion of pulsating auroras in the midnight sector is variable in direction; if observed, the motion of pulsating forms in the early evening sector is generally westward.

Extensive searches for conjugate pulsations within television data acquired on the 18 aircraft missions described by Stenbaek-Nielsen *et al.* (1973) resulted in the location of a number of exactly in-phase pulses. Many of these are shown in Figure 16. These examples all come from sub-visual or barely visible pulsating auroras equatorward of the main display, as shown in Figure 17. Most of the examples of in-phase conjugate pulsations come from an interval only a few minutes long, evidently when the two aircraft acquiring the data were exactly conjugate.

It is not obvious whether the failure to find more examples is due to the aircraft not flying exactly conjugate paths or due to relative rarity of identifiable conjugate pulses. The searches do seem to indicate that conjugate out-of-phase pulses do not occur. Whereas those pulses occurring simultaneously in the two hemispheres require a mechanism in the equatorial plane or at least triggered by some phenomenon located there, the majority of individual auroral pulsations observed could result from ionospheric processes of local nature, though the general conditions dictating when and where pulsations will be observed are likely to be mainly magnetospheric.

Rocket measurements of precipitating electrons creating a series of optically observed periodic pulsations by Bryant *et al.* (1971) showed a dispersion of energies that indicated a near-equatorial, rather than ionospheric, location of the modulation mechanism. Their results also indicated that the modulation of the highest energy electrons was greater than that of the lowest energy electrons, so that there was a hardening of the spectrum near the peak of each pulse. Measuring both proton and electron fluxes above an intense pulsating aurora, Johnstone (1971) found that the proton intensity increased with the electron intensity and that the proton spectrum softened as the electron spectrum hardened. Johnstone noted that this result was compatible with a precipitation mechanism proposed by Swift (1970) which accelerates electrons at the expense of energy in trapped protons and which operates most effectively just above the ionosphere.

Satellite-borne measurements of electrons at low altitude above the postmidnight region where pulsating auroras occur and which almost certainly pertain to pulsating auroras show fluctuating precipitating electron fluxes up to several erg $(\text{cm}^2\,\text{s sr})^{-1}$ (Frank *et al.*, 1976). Except in the loss cone, the measured electron intensities were isotropic in the range $50\,\text{eV} \leq E \leq 15\,\text{keV}$. Intensities of field-aligned energetic electrons ($E > 45$ keV) were never found to exceed the intensity of electrons with pitch angles at 90°, although the energy fluxes of precipitating electrons in the $50\,\text{eV} \leq E \leq 15$ keV range occasionally slightly exceeded the flux of those at pitch angle 90°. Whalen *et al.* (1971) observed isotropic fluxes or ones

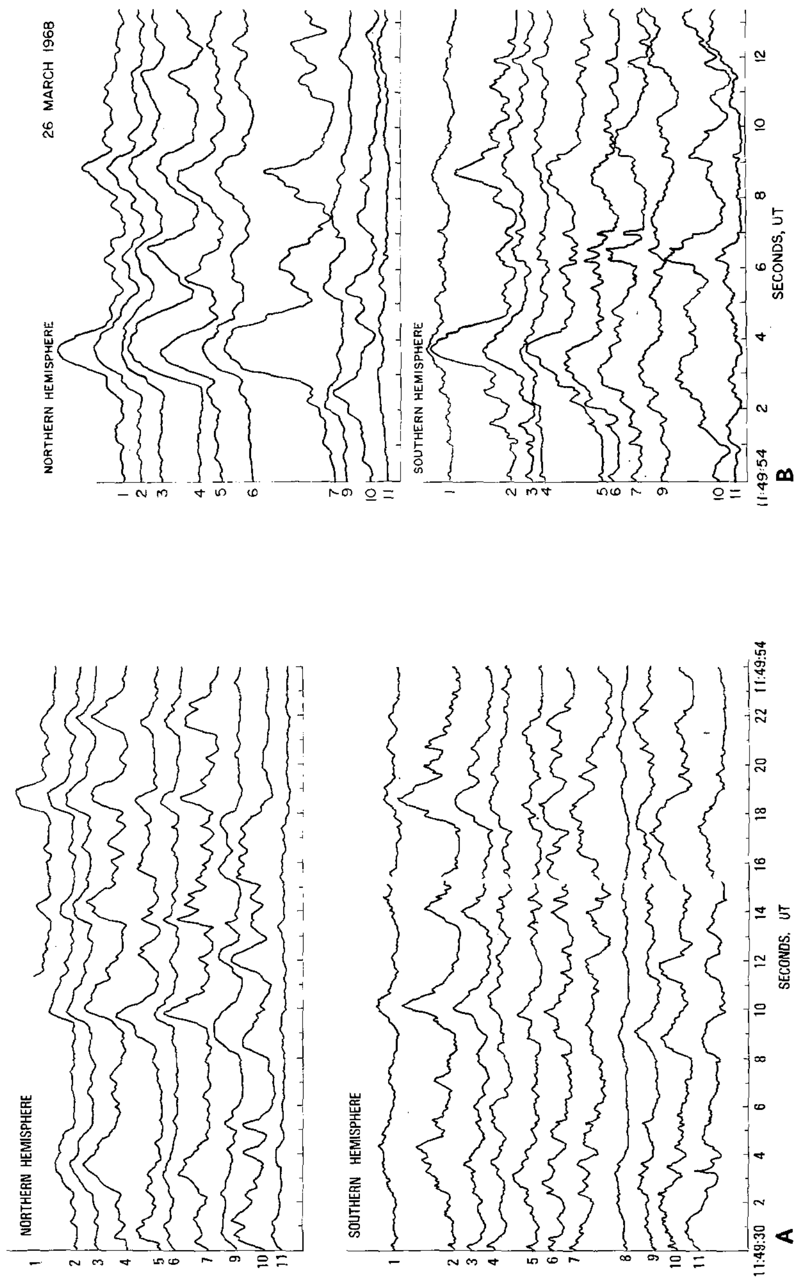

26 MARCH 1968
NORTHERN HEMISPHERE
SOUTHERN HEMISPHERE
SECONDS, UT
11:49:30
11:49:54
A
B

Fig. 16 A, B.

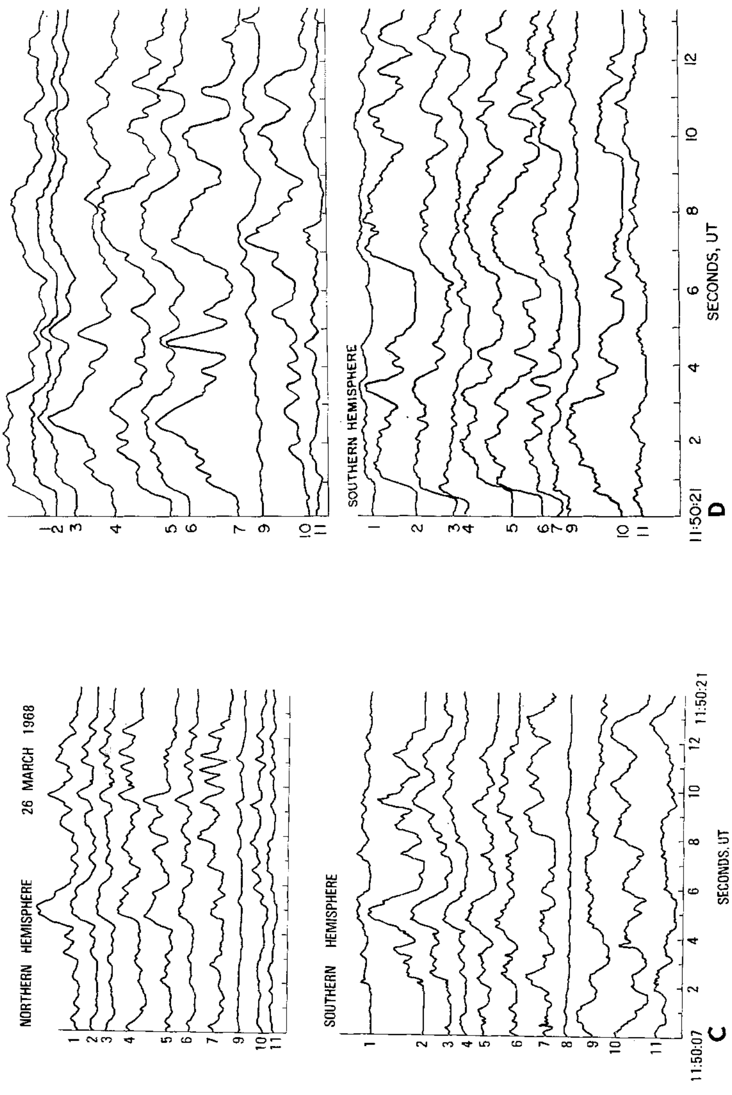

NORTHERN HEMISPHERE
26 MARCH 1968
SOUTHERN HEMISPHERE
SECONDS, UT
11:50:07
11:50:21
C
D

Fig. 16 C, D.

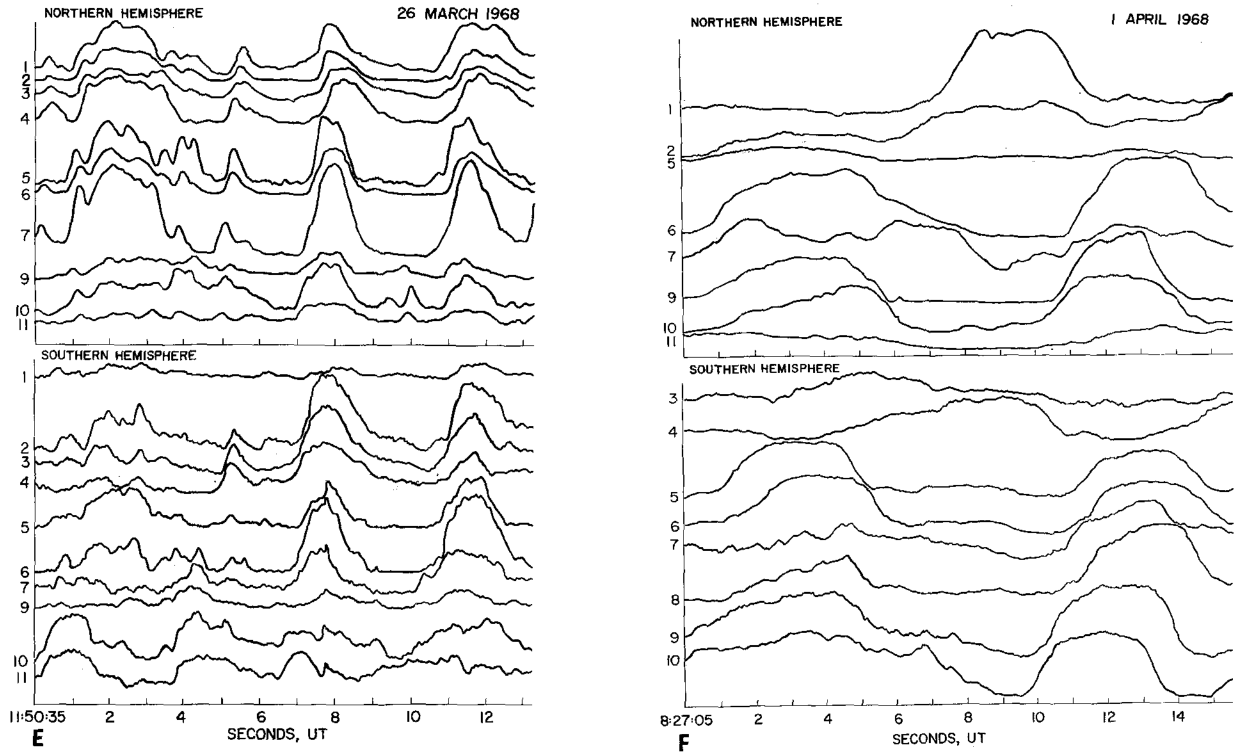


Fig. 16 E, F.

Fig. 16 A–F. Parts A–F show a number of individual pulsations that can be identified in simultaneous television data acquired in the north and south hemispheres. Traces numbered 1–11 were obtained by a photocell placed before a TV monitor successively in a 4-3-4 array commencing at upper left. Parts A–E collectively form an almost unbroken sequence in time.

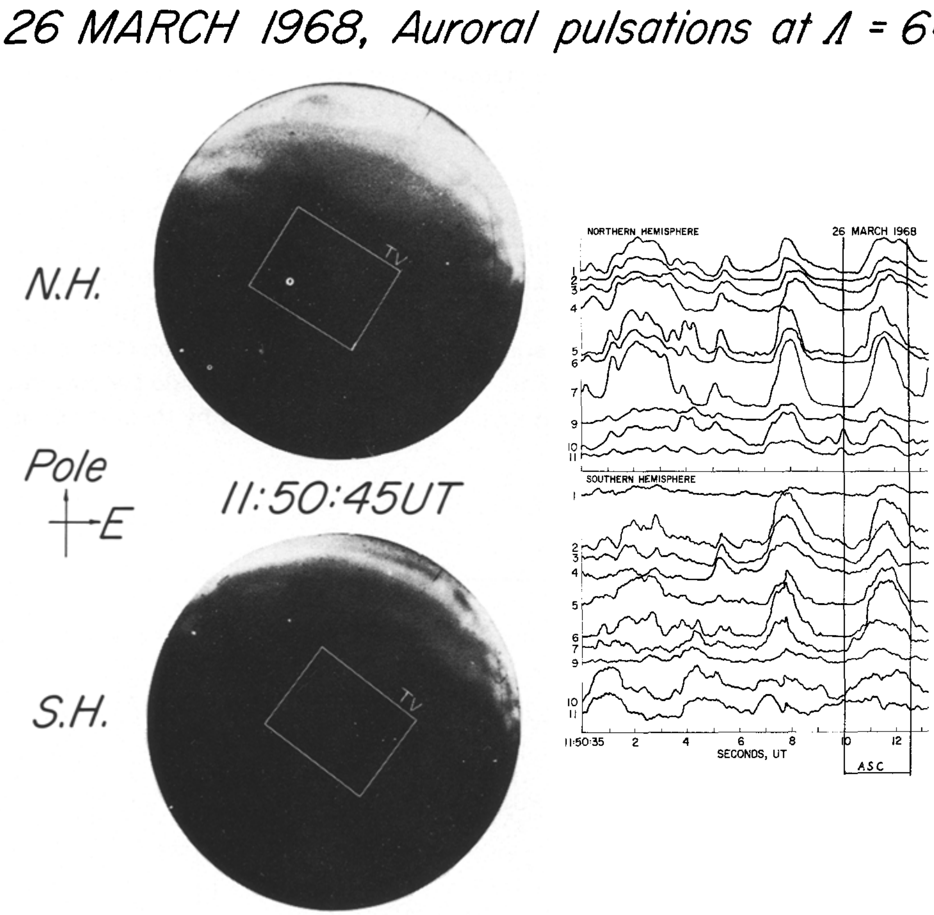


Fig. 17. Conjugate all-sky photographs showing the location of the television fields of view equatorward of the main body of pulsating aurora at the time the data shown in Parts A–E of Figure 16 were acquired. Part E of Figure 16 is reproduced at right, the block marked ASC is the time interval of the synchronized all-sky camera exposures.

peaked near 90°. As did Bryant *et al.* (1971), Frank *et al.* (1976) observed greater fluctuations in the more energetic electrons than in the low-energy electrons. Fluctuations in the range 2–10 s were found in both the $50\ \text{eV} \leqslant E \leqslant 15\ \text{keV}$ and $E > 45\ \text{keV}$ ranges. Lui *et al.* (1977) found a relatively uniform electron precipitation above the diffuse aurora largely below 13 keV and with isotropic pitch angle distribution. Near the equatorward boundary they found a substantial contribution by protons, but in some cases even the sum of proton and electron flux could not account for the observed intensity of aurora there.

The satellite- and rocket-borne observations showing greatest modulation at the higher energies are compatible with the report by Brown *et al.* (1976), indicating substantial difference in the altitude of pulsating aurora and the background in which it is embedded. Additional measurements of the altitudes of pulsating auroras by Stenbaek-Nielsen and Hallinan (1978) do not disagree with the results of Brown *et al.* (1976) except that the median altitude of lower borders of pulsating aurora is found to be higher (98 km, as compared to 92 km).

The measurements of altitude do not prove that the schematic drawing in Figure 18 is correct since, strictly speaking, the altitude of the diffuse background has not been measured. However, when the diffuse, but non-pulsating, aurora temporally and spatially associated with pulsating aurora has enough structure to permit a measurement of altitude by triangulation, the non-pulsating portion of the display is found to be at relatively high altitude, as indicated by Figure 18. Earlier observations of the brightness fluctuations by Shepherd and Pemberton (1968) and of temperatures (Hilliard and Shepherd, 1966) in pulsating auroras do support the correctness of Figure 18, though the variation in altitude found by them is not as great as indicated in Figure 18.

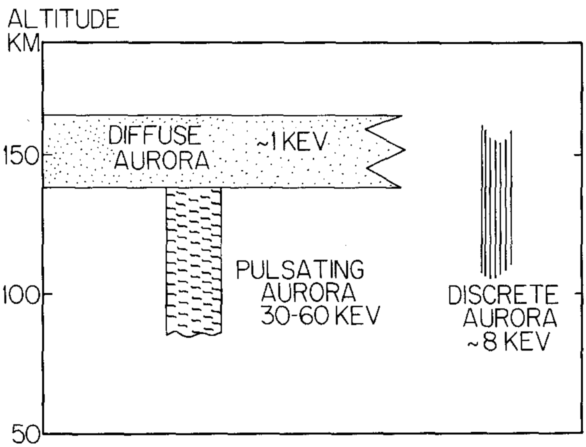


Fig. 18. Schematic drawing illustrating altitude differences typical of discrete and pulsating aurora and the probable geometric relationship between pulsating aurora and the higher-altitude diffuse background wherein it occurs (after Brown *et al.*, 1976).

The paper by Stenbaek-Nielsen and Hallinan reports the interesting new finding that some pulsating auroras appear to have extremely limited height extent, so limited, in fact, to be unexplained by even monoenergetic electrons impacting the atmosphere. These auroras all have small width – otherwise the technique would not permit measurement of the height extent – so are not necessarily representative of all pulsating auroras.

Through measurement of Doppler line widths in pulsating auroras, Zwick and Shepherd (1973) have found that when a pulsation occurs on a particular flux tube, the background emission on that flux tube changes. Hence, they infer that whatever mechanism causes the pulsation also modulates the background emissions.

3.4. Interpretation of observations

Several of the reported characteristics of pulsating aurora point toward a causative mechanism operable in or near the equatorial plane. Among these are the observed hardening of the electron spectrums concurrent with the development of the 'on-phase' of pulsations and the observed simultaneous appearance of conjugate pulsations. A mechanism proposed by Coroniti and Kennel (1970) and involving diffusion of electron pitch angles by wave turbulence in the equatorial plane satisfies the requirements of many of the observations. Pulse shapes reported by Whalen *et al.* (1971) and Royrvik and Davis (1977) are compatible with the Coroniti and Kennel mechanism, as are the temporal variations of particle fluxes described by Frank *et al.* (1976). The mechanism does not predict the geometry of pulsating auroras. It does not account for the hardening of the electron spectrum during the on-phase reported in several papers, the relationship between proton and electron spectra reported by Johnstone (1971) nor the near-zero height extent of some pulsating auroras found by Stenbaek-Nielsen and Hallinan (1978). In fact, certain of these observations seem to require mechanisms operative in or near the ionosphere, rather than near the equatorial plane.

In order to fully understand pulsating aurora, it may be necessary to learn the nature of several different mechanisms or processes. One is clearly of global substorm nature and leads to the injection of energy or particles into the field lines inside the trapping boundary. Once that mechanism has begun to operate, then precipitation mechanisms such as that of Coroniti and Kennel (1970) or Swift (1970) can come into play. The diversity in scale size, shape and temporal variation suggest the possibility of more than one precipitation mechanism being operable. There may be modulating mechanisms which are strictly ionospheric, though most of the evidence seems to point to those operating in the magnetosphere.

4. Transitions Between Types of Auroras

4.1. Spatial and temporal relationships

Topside images of auroras typically show a merging of discrete and diffuse auroras near the midnight sector, especially if the level of activity is high (Lui *et al.*, 1973; Snyder *et al.*, 1974). However, in the evening sector quite separate regions exist. The discrete aurora in this region is always on the poleward side and may be separated by several tens of kilometers from the diffuse region. However, even in the evening sector, short-lived and small-scale pulsating arcs or arc-like segments sometimes are observed in close association with discrete auroras lying in the poleward 'discrete' region. Typically these pulsating auroras pulse on and off only a few times and then appear no more. In addition to the short-lived pulsating auroras that sometimes are seen in association with discrete auroras, the discrete aurora often exhibits various types of bright, fast-moving pulsing behavior; flickering is one example (Beach *et al.*, 1968).

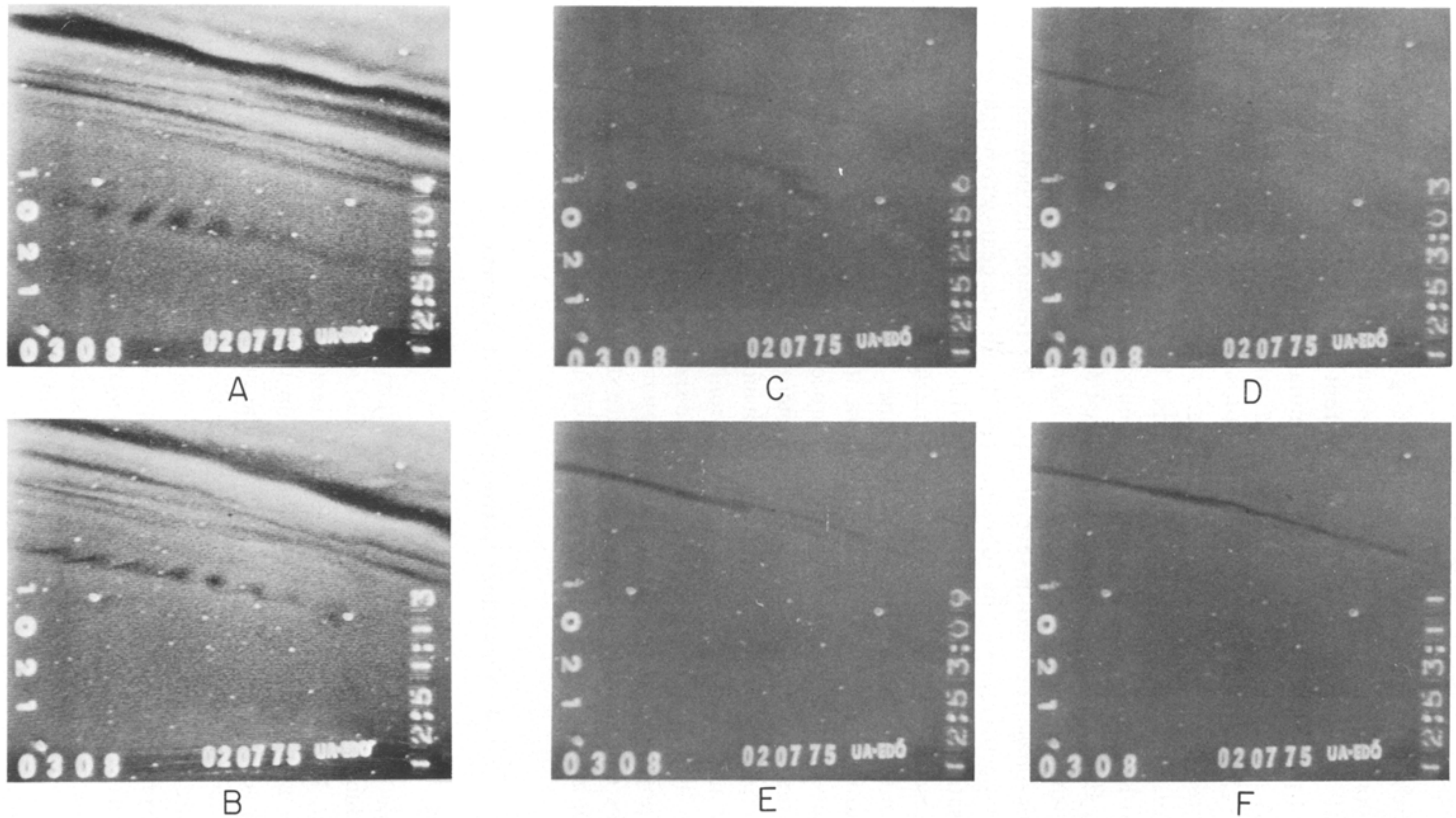


Fig. 19. Television photographs (12° × 16° field of view) of the magnetic zenith region above College, Alaska, showing 'black aurora'. Parts A and B show an interconnected row of spots identical to curls except showing the opposite rotation sense. Parts C–F show thin eastward-drifting arc-like voids in the otherwise uniform layer of emission. These photographs were acquired on 7 February, 1975 at the times shown by the numerals on the right-hand side of each image (after Royrvik, 1976).

In general, the temporal transitions that occur in the evening sector between discrete and pulsating are reversible and without any radical changes that seem to signal a new development in the course of the display at a particular location. However, in the midnight and morning sectors, when pulsating patches are observed to develop toward an east-west alignment, this usually indicates a transition resulting in bright, discrete auroras being observed within the half-hour.

4.2. 'BLACK AURORA'

When pulsating forms tend to develop with arc-like alignment in the east-west direction and the pulsations cease, it is common to observe widespread, relatively uniform emission in which black void areas appear. An excellent example is shown in Figure 19. The 'black aurora' is a lack of emission in well-defined regions within an otherwise uniform, diffuse emission. It is most commonly observed near the magnetic zenith, but the fact that it is sometimes observed as much as 30° off-zenith indicates that the emission in which the 'black aurora' occurs has limited height extent, otherwise the void regions could not be observed.

Observations by Nazarchuck (1975) and Oguti (1975) suggest that when the 'black aurora' appears, the aurora may be transitional from discrete to diffuse as well as from pulsating diffuse to discrete.

The 'black aurora' is transitional in another sense. It shows evidence of shear, not as much as discrete aurora, but more than diffuse aurora. The example in Figure 19 is particularly striking; the vortex street array is similar to the curls described by Hallinan and Davis (1970) except that it shows clockwise rotation and thereby implies an excess of positive charge in the holes. This transitional behavior of 'black aurora' emphasizes again one of the key distinctions between discrete aurora and pulsating diffuse aurora – strong electric fields are associated with discrete auroras, but not with pulsating diffuse aurora.

Acknowledgments

I thank D. W. Swift, T. J. Hallinan, and H. C. Stenbaek-Nielsen for many useful discussions and suggestions on this manuscript. This work was supported by grant number ATM 77-01370 from the Atmospheric Sciences Section, National Science Foundation, Washington, D.C. and by the National Aeronautics and Space Administration.

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