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By
D. M. SHIPSTONE, B.Sc., Ph.D.
Department of Physics, University of Sheffield
and
British Antarctic Survey

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ABSTRACT

RADIO-AURORAL observations at 71·3 MHz were made from Halley Bay, British Antarctic Territory, during the International Quiet Sun Year using a system of three rhombic aerials. Comparison with observations made during the International Geophysical Year (Harrison, 1962) shows that, between these periods, there were no significant changes in the location of the echoing region and also, after due allowance for changes in equipment sensitivity and in the level of magnetic disturbance, no significant changes in the behaviour of the radio aurora itself.

Discrete and diffuse radio aurorae were found to occur in separate oval distributions which were eccentric with respect to the geomagnetic pole. It is suggested that the diffuse and discrete radio aurorae may be associated with the precipitation of energetic protons and electrons, respectively, into the upper atmosphere.

It is shown that the radial velocities of diffuse radio aurorae cannot be those of ion-acoustic waves (Farley, 1963*b*). A variation with geomagnetic latitude in the time at which the radial motions of radio aurorae reverse direction was found and this agrees well with observations from other Southern Hemisphere stations. These observations are consistent with the suggestion that radio aurorae move in the direction of the electron current in the ionosphere.

It is demonstrated conclusively here that radio aurorae are frequently not due to radio-wave reflections from aurorae visible to the naked eye. Both discrete and diffuse radio aurorae extend, on average, approximately 1° of latitude equatorwards of homogeneous arcs.

Associations have been found between radio aurorae and a number of types of sporadic E. No significant association was found between radio aurorae and spread F. A negative correlation has been found between radio aurorae and ionospheric black-outs observed in the evening, and this has important implications for riometer studies of auroral absorption.

CONTENTS

I. INTRODUCTION

ROUTINE observations of the radio aurora and meteors at Halley Bay, Antarctica (geographical co-ordinates lat. 75·5° S., long. 26·6° W.) commenced in the International Geophysical Year using a 71·3 MHz radar designed and built at Jodrell Bank, England (Harrison, 1962). A rotating aerial system, comprising two six-element Yagi aerials mounted horizontally on a tower, was used during the I.G.Y. to locate the echoing region. Further observations were made in 1962 by J. S. Marsden using a fixed aerial system consisting of three rhombic aerials which were directed towards the limbs and centre of the echoing region determined by Harrison. This report is concerned with the third series of observations, undertaken as part of the International Quiet Sun Year research programme, which completed the observation of the radio aurora at Halley Bay over half of the solar cycle, including the periods of maximum and minimum solar activity.

1. *Mutual interference problems*

At a meeting held at the Radio Research Station, Slough, Buckinghamshire, England, to discuss problems of mutual interference with the I.Q.S.Y. ionospheric team for Halley Bay, the decision was taken to re-site the radio-echo equipment in a position west of the ionospheric equipment. As the radio-echo transmissions were in a southerly direction, interference problems would have been severe had the old site, to the north of the ionospheric aerial system, been used. The site finally chosen for the radio-echo hut was 300 yd. [274 m.] west of the ionospheric hut as shown in Fig. 1. It was further decided that the best way of avoiding interference with most of the ionospheric equipment would be to synchronize the operation of the radio-echo equipment with the mains cycle as were the ionosonde and the absorption equipment. A pulse repetition frequency of 100 per sec., twice the mains frequency, was chosen for the auroral radar.

2. *Modification and installation of the equipment*

The radar employed was that used in the previous observing programmes at Halley Bay, though with many modifications. The radar was returned to the University of Sheffield from Halley Bay in 1963 to effect these modifications and also for a complete overhaul. Regrettably, packing facilities at Halley Bay were inadequate and the radar was badly damaged on the journey.

The repair of the radar commenced in July 1963 and was completed by the end of November when the radar was despatched to Halley Bay. During that period the receiver noise figure was greatly improved but modifications to the transmitter to reduce frequency pulling when the aerials and feeders became loaded with hoar frost could not be completed before the time of despatch. Modification of the radar to synchronous operation with the mains cycle had not been attempted at that stage.

The equipment arrived safely at Halley Bay at the end of January 1964 and was installed in a fibre-glass hut. The system of three rhombic aerials which was erected was similar to that employed by J. S. Marsden in 1962, the aerials being directed 55° east of south, due south and 55° west of south, that is, towards the limbs and centre of the echoing region observable from Halley Bay. The heights of the aerials were, on average, 2·25 wave-lengths. Throughout the period of observation these heights were gradually reduced as the surrounding snow level rose due to the accumulation of drift.

To reduce interference due to snow static, the aerial feeders were run at a height of 12 ft. [3·6 m.] above the snow surface. Interference from this source was never serious. To further reduce interference due to snow static and to reduce detuning of the transmitter due to hoar-frost deposits, the total length of the feeder run external to the hut was kept reasonably short, the length being 80 ft. [24·4 m.] or approximately 6 wave-lengths. By using the same length of feeder between the aerial switch and the matching stub on each of the three feeder runs it was found possible to ensure that the impedances presented to the transmitter by the different aerials remained sufficiently similar for three-aerial operation to be maintained, except on rare occasions when hoar-frost conditions were exceptionally severe.

The whole of winter and spring of the first year, 1964, was spent in overhauling the radar and in carrying out those modifications which had not been completed before the equipment left Sheffield. Synchronizing the radar transmissions with the mains cycle entailed the re-designing of much of the pulsed circuitry. Pulses for controlling the transmitter, triggering the time base and suppressing the receiver were derived from the mains cycle and not, as in previous years, from a standardized 600 Hz oscillator. Range marks were provided by a pulsed Hartley oscillator, also triggered from the mains cycle. The 600 Hz oscillator

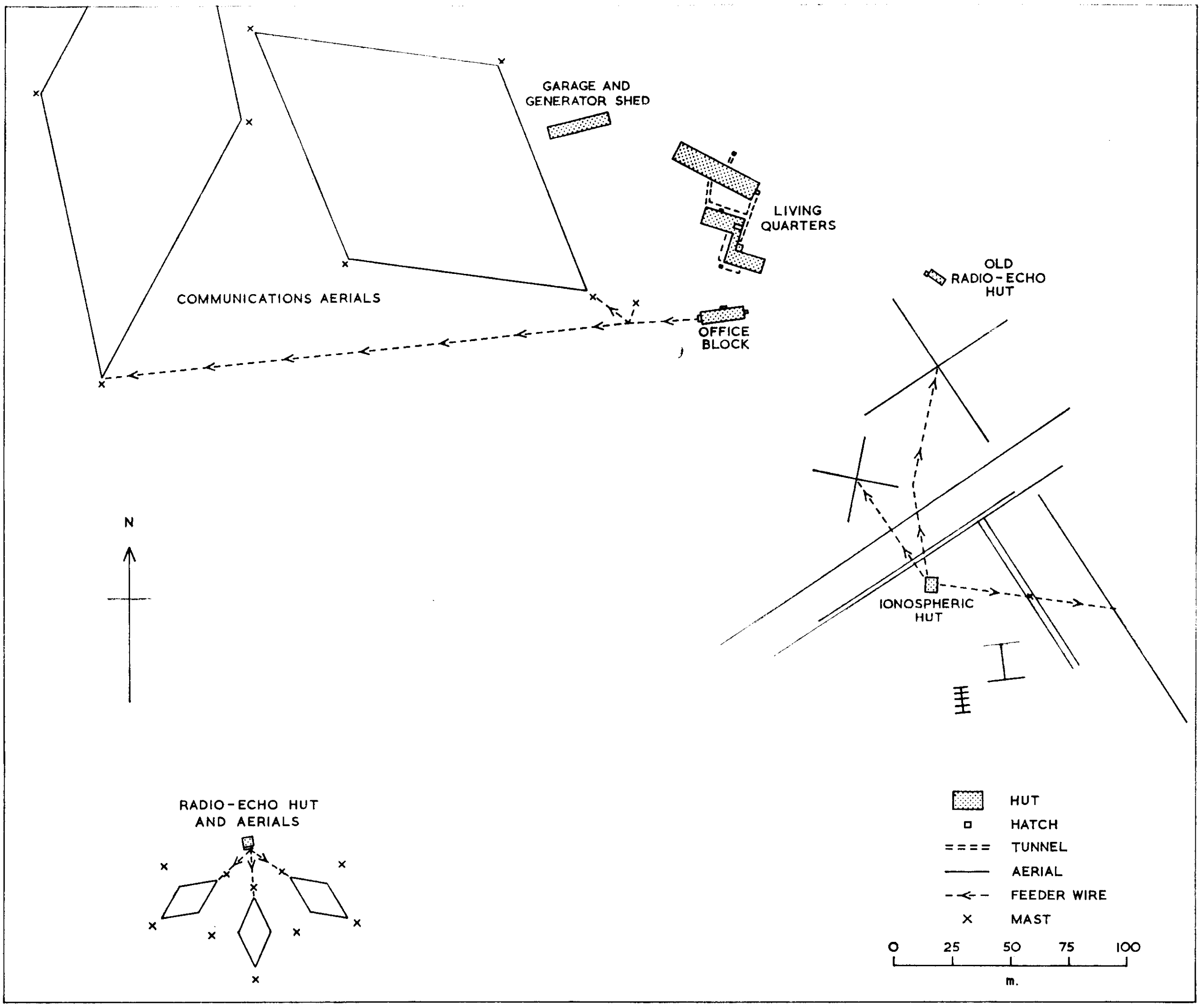

FIGURE 1

The southern part of the British Antarctic Survey station at Halley Bay in 1965.

was retained for calibration of the pulsed Hartley oscillator. The transmitter modifications were completed, two stages of amplification being added to buffer the master oscillator against changes to the load impedance of the power amplifier which resulted from deposits of hoar frost on the aerials and feeders. A phase shifter was built into the radar so that its transmissions could be exactly synchronized with those of the ionosonde and the absorption equipment, and it became practicable to derive, in the radio-echo equipment, suppression pulses against the ionospheric team's transmissions.

As in previous years, the radar returns were recorded continuously on 35 mm. film. The display contained two cathode-ray tubes orientated at 90° and 45° to the film motion. The former tube was intensity modulated and displayed the radio-auroral activity in rectangular range–time coordinates. Echo amplitudes were displayed on the other tube. Echoes from different ranges tended to overlap on the amplitude display particularly at times of high activity, though it was usually possible to determine the amplitudes of the larger echoes. The use of Ilford 5B52 film, which has an anti-halation backing, and short-persistence tubes in the display produced a recording system which was not easily fogged. The brightness of the display tubes was so adjusted that background noise was just recorded. Time was indicated on the film records by a watch, mounted in the display, which was illuminated at 1 min. intervals. Three lamps in the display indicated the aerial on which the radar was operating. A film speed of 22·8 cm./hr. was used throughout.

To distinguish between noise spikes and sharp echoes, either from meteors or discrete radio aurorae, pulses were transmitted in pairs, the separation in time of the echoes being equivalent to a 50 km. separation in range. Such a distinction was essential as most interference on the base was synchronized to the mains cycle, as were the radar transmissions. The use of a receiver pass-band several times the optimum width for the pulse length used permitted further discrimination against noise spikes. The broad receiver band width ensured that the noise spikes from transient interference were of shorter duration than the echoes and after video-amplification the signals were passed through a width discriminator, the output from which was used to intensity modulate the display cathode-ray tubes.

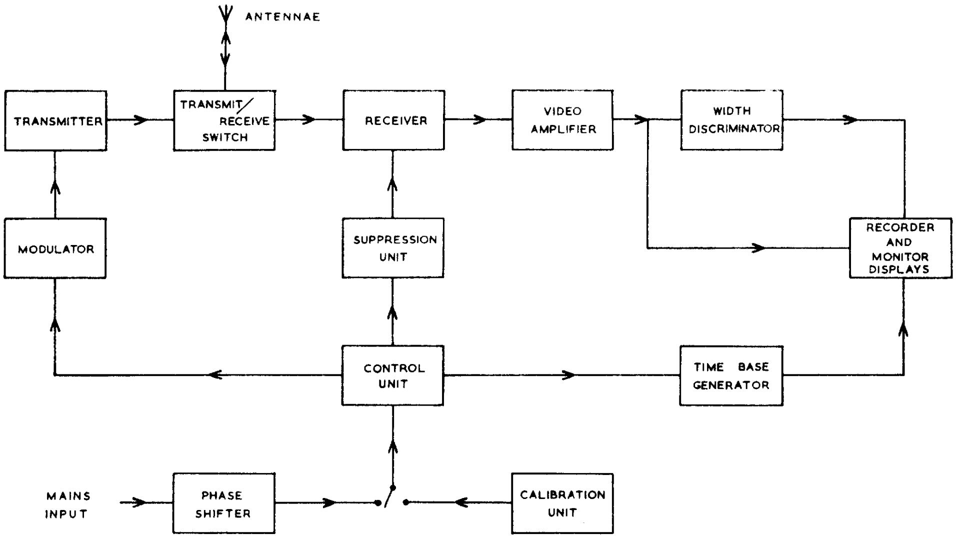

FIGURE 2

Lay-out of the main units of the radar.

A block diagram of the radar is shown in Fig. 2. The most important parameters of the equipment were as follows:

Radio frequency	71·3 MHz
Peak power transmitted	7·5 kW
Pulse length	30 μsec.
Pulse-repetition frequency	100 pairs/sec.
Separation of the pairs	333 μsec.
Receiver band width	80 kHz
Intermediate frequency	5 MHz
Local oscillator frequency	76·3 MHz
Antenna impedance	600 Ω
Receiver sensitivity	4 μV r.m.s. C.W. when fed into the receiver, through the transmit-receive switch, doubled the receiver output due to noise alone
Antenna beam width—horizontal	14° to half-power points
Antenna beam width—vertical	6° to half-power points
Elevation of main lobe axis	5°

The aerial polar diagrams were computed by Marsden and are shown in elevation and azimuth in Fig. 3.

3. *Normal operation*

Operation on the south rhombic alone commenced on 20 January 1965 but, due to the arrival of the relief ship, bad weather and many equipment failures, it was not possible to commence operation on all

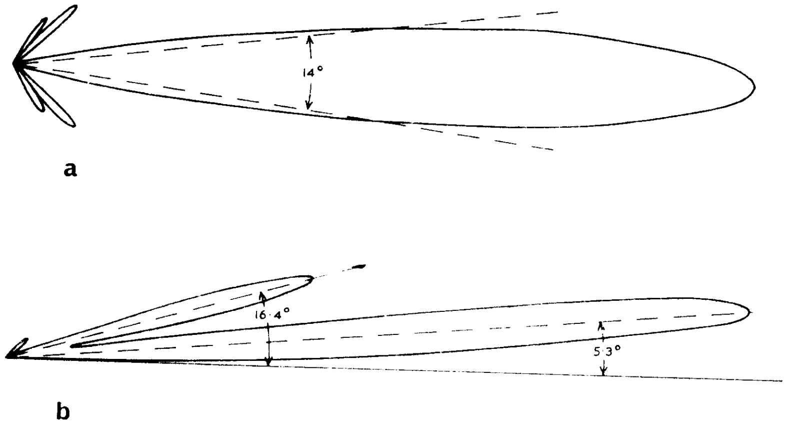

FIGURE 3
Horizontal (a) and vertical (b) aerial amplitude polar diagrams (forward direction only).

three aerials until 11 April. From that date until 20 January 1966, when operation ceased, continuous observations were maintained for 95 per cent of the time, though on occasions it was not possible to operate on all three aerials. The graphs in Fig. 4 show, for each of the three aerials, the time satisfactorily observed as a percentage of the time for which the aerial was in service.

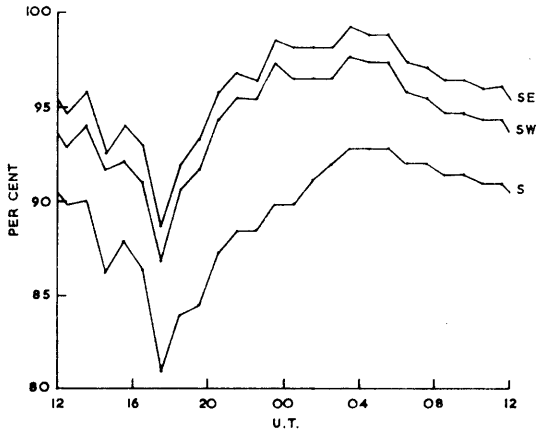

FIGURE 4
The percentage of the time that each antenna was in service during which satisfactory observations were made.

Under normal circumstances the radar was switched between aerials every 4 min. so that a complete cycle of observations on the three aerials occupied 12 min. Facilities were provided for altering this sequence to omit one or two of the aerials. When one aerial required repair, observations were continued on the other two. Occasionally, exceptionally heavy hoar-frost deposits produced marked differences between the aerial impedances and operation on all three rhombics became impossible. At such times preference was always given to the south-east aerial as the great majority of the radio-auroral echoes were obtained from that direction. Attempts were always made to clear the aerials and feeders of hoar frost by banging the halyards but these were frequently unsuccessful.

At times when hoar frost was present, which in winter included most periods free from blizzards, the radar was inspected three or four times each day. Whenever it became necessary to alter the tuning of the transmitter into the aerials, this was first optimized for each aerial in turn and the current, I_0, delivered into each of the aerials was noted. The tuning was then re-adjusted to obtain the largest current output, I, compatible with operation on all three aerials. If it is now assumed that when the current was I_0 the power delivered into the aerials was the optimum power, P_0, delivered by the transmitter into a matched load, then a first approximation to the actual power transmitted, P, is given by

$$\frac{P}{P_0} = \left(\frac{I}{I_0}\right)^2.$$

For the mid-winter months, June and July, the values of this ratio were calculated for periods between routine checks by linear interpolation. The mean values of the ratio, calculated for 2 hourly intervals, are given in Fig. 5. The variation of mean power output throughout the day was very small and no correction has been made for this in the analysis which follows.

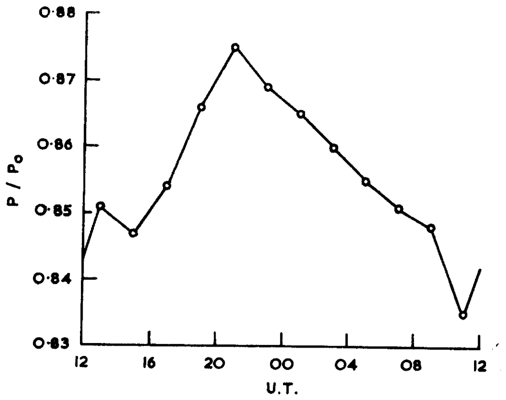

FIGURE 5

The diurnal variation in the ratio of the actual power transmitted, P, to the optimum power, P_0, during June and July 1965.

Daily checks were made of the receiver sensitivity and of the transmitter tuning. A C.W. signal of known amplitude was fed into the receiver from a signal generator tuned to optimize the receiver output. The output of the receiver was recorded to give a routine measurement of the receiver sensitivity. A communications receiver was tuned to the signal-generator frequency and the communications receiver, thus calibrated, was used to check the tuning of the transmitter. The modifications made to the transmitter were apparently successful as there was no evidence of frequency pulling throughout the period of operation.

To calibrate the range scale, the frequency of the 600 Hz oscillator was first set accurately by tuning out the beats produced between a 600 Hz tuning fork and a loudspeaker fed by the oscillator. Pulses derived from the oscillator were then differentiated and the wave form obtained was used both to trigger the pulsed Hartley oscillator and to intensity modulate the oscilloscope on which the output from the pulsed oscillator was displayed. The intensity-modulated wave form provided a means of checking the frequency of the pulsed Hartley oscillator.

II. ANALYSIS OF THE FILM RECORDS

1. *Radio-auroral observations*

The 35 mm. film records were scaled with the aid of a d-Mac pencil follower after projection onto the large plane surface of the instrument. Basically, a servo-mechanism in the instrument guides a sensory device, mounted on a gantry beneath the plane surface, to the location of the "pencil", a probe which emits a low-frequency signal. The position of the sensor gives the location of the pencil in the rectangular coordinate system of the instrument. The pencil is placed at a point which is to be recorded and, on depression of a foot switch, the pencil follower punches out in digitized form the coordinates of the point in the instrument's coordinate system.

The set of points defining the rectangular range–time coordinate system on the film records was recorded before the analysis of the results for each hour. A computer was then used to derive the range–time coordinates of the radio aurorae from the pencil-follower output. Prior to the scaling of the results in each

4 min. interval, points at the ends of the 250 km. range marker, which was used as the base line, were recorded to allow correction for any drifts in the trace positions on the display tubes and for drift of the film transport of the projector.

The following parameters were recorded for each radio aurora: aerial, type of echo, amplitude, minimum range, maximum range, range of peak activity, maximum velocity, mean velocity and time of occurrence. Echoes observed on each of the three aerials were treated separately.

Following the method adopted by Marsden, auroral echoes of a particular type which were separated by more than 50 km. in range were treated as separate events. Echoes of different types were treated as distinct events whatever their range separation. Three types of radio aurora were distinguished. These were classified as "discrete" if the two transmitted pulses could be resolved in the echoes and as "diffuse" if the transmitted pulses could not be so distinguished. Where discrete structure existed against a diffuse background the radio aurorae were classified as "structured diffuse".* This classification was adopted for the analysis described here long before the fourteenth General Assembly of the I.U.G.G. in 1967 and differs somewhat from the new classification proposed by the working group formed at that assembly. According to this new classification, the diffuse and structured diffuse radio aurorae observed from Halley Bay should have been grouped together as type B_1, whilst the discrete radio aurorae should have been subdivided, where possible, into types B_2 and B_3.

An index of amplitude was assigned to each event using the classification employed by Harrison (1962). Three amplitude classes were identified as given in Table I. Due to the use of a fixed aerial system, it was frequently only possible to determine the echo amplitudes at the time of switching between aerials when the change in the distribution of radio aurorae temporarily reduced the overlap of echoes on the amplitude display.

TABLE I

RELATION BETWEEN RADIO-AURORAL INDICES AND ECHO AMPLITUDES

Amplitude index	*Corresponding peak amplitude of echo*
1	Echo just detected
2	Echo of moderate amplitude but below the saturation level of the recording system
3	Echo reaching the saturation level of the system at about 10 times the noise level

The three range parameters listed above were recorded for one particular instant in time and, as such, represent mean values for the position of the echoing centre during the 4 min. period of observation. The range of peak activity is usually, but not necessarily, about half-way between the maximum and minimum ranges. The same parameters were recorded for a group of echoes which could not be resolved due to insufficient range separation between the component echoes. Such a group of echoes was treated throughout as a single event.

Where one distinct reflecting centre comprised the recorded event, the maximum and mean velocities of the echoing centre were usually identical, though at times pronounced changes occurred in the velocity of a radio aurora during the 4 min. observing period. The main purpose of using two velocity parameters, however, was to distinguish between the maximum and mean velocities of the component echoes of a group.

The recorded time of occurrence of an echo was the time at the commencement of the 12 min. period in which the echo occurred, and can therefore be in error by as much as 12 min.

The digital output of the pencil follower was processed in the University of Sheffield Mercury computer to convert the range and velocity measurements from the coordinate system of the pencil follower to range–time coordinates.

To reduce statistical fluctuations in some of the analyses described here, the data have been grouped into 24 min. intervals and not the 12 min. intervals as scaled from the film records. This type of analysis was carried out at the Atlas Computer Laboratory, Chilton, Berkshire, using a programme developed by

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* Examples of the three echo types are shown in Plate I.

Marsden. The Atlas computer was used in conjunction with the SC4020 graph plotter at the Atomic Weapons Research Establishment, Aldermaston, to produce the radio-auroral results in graphical form.

Hourly amplitude indices have also been used in some of the analyses and were the maximum amplitude indices recorded for echoes of each type in each hour. Separate indices were derived from observations made on each of the three aerials and for the diffuse and discrete radio aurorae. There is some evidence to suggest that the structured diffuse echoes were obtained when diffuse and discrete radio aurorae occurred simultaneously in the same range interval, and in deriving the hourly amplitude indices these echoes have been included with both the diffuse and discrete types. The effects of this procedure on the indices assigned to the diffuse and discrete echoes were very small since an hour which contained structured diffuse echoes of any given amplitude usually also contained both diffuse and discrete echoes of that amplitude. Since each hour which contained radio aurorae was assigned six numbers, these will be referred to as six-figure indices.

A second set of hourly indices was obtained by assigning those echoes obtained with the south aerial to both the east and west limbs of the echoing region. The resulting four-figure indices were closely similar to the four-figure indices derived by Harrison (1962) and have been used in the comparison of observations from the I.G.Y. and I.Q.S.Y.

2. *Meteor observations*

From 20 January to 11 April 1965 only the south rhombic was in use. Throughout this period the number of meteors occurring in the first 4 min. of each 12 min. observing period was recorded. Hourly sums of meteor counts were derived and tabulated. Each hour was accepted or rejected according to whether more or less than 30 min. had been satisfactorily observed. Where more than 30 min. but less than the full hour had been observed, the count was corrected for the loss of recording time. From 11 April 1965 to 20 January 1966 continuous observations were made on the south-east aerial and, for most of that period, also on the south and south-west aerials. Since most radio aurorae were observed on the south-east aerial, meteor counts were made for that aerial only, to provide a continuous check on the radar sensitivity on that aerial.

3. *Tabulated data*

Copies of tables of the hourly four-figure indices of radio-auroral activity, described above, and of the hourly meteor rates, corrected for loss of observing time as described above, are obtainable on request from the World Data Centre, Slough, Buckinghamshire, England.

III. LOCATION OF THE ECHOING REGION

THE use of a rotating aerial system enabled Harrison (1962) to determine accurately the location of the echoing region observable from Halley Bay. This was found to fit very closely, at a height of approximately 110 km., the contour derived from the condition of specular reflection from columns of ionization aligned with the Earth's magnetic field. Harrison's fig. 13, comparing the observed position of the echoing region with two specular contours, is reproduced here as Fig. 6. A most interesting feature is the large range of geomagnetic latitudes (centred dipole coordinates) covered by the echoing region which extends from lat. 67° to 72° S. In Fig. 7 the position of the echoing region is shown in corrected geomagnetic coordinates (Hakura, 1965).

The advantage of the system of fixed aerials used during the I.Q.S.Y. was that individual echoing centres were observable for moderately long intervals, normally of up to 4 min. but depending upon the echo duration. The use of fixed aerials, however, rendered a check on the contour position impossible except at its point of closest approach to Halley Bay. The south rhombic used during the I.Q.S.Y. was directed at the point of closest approach of the echoing region. In Fig. 8 the distribution in range of the echoing centres observed with that aerial during the I.Q.S.Y. is compared with the corresponding distribution found by Harrison during the I.G.Y. The tail at large ranges in the I.Q.S.Y. distribution arose because, in the absence of information on azimuths, it was impossible to determine whether or not the echoes obtained came from the point of closest approach of the echoing region. The close agreement between the positions of the main peaks in the two distributions shows that no significant changes in the position of this part of

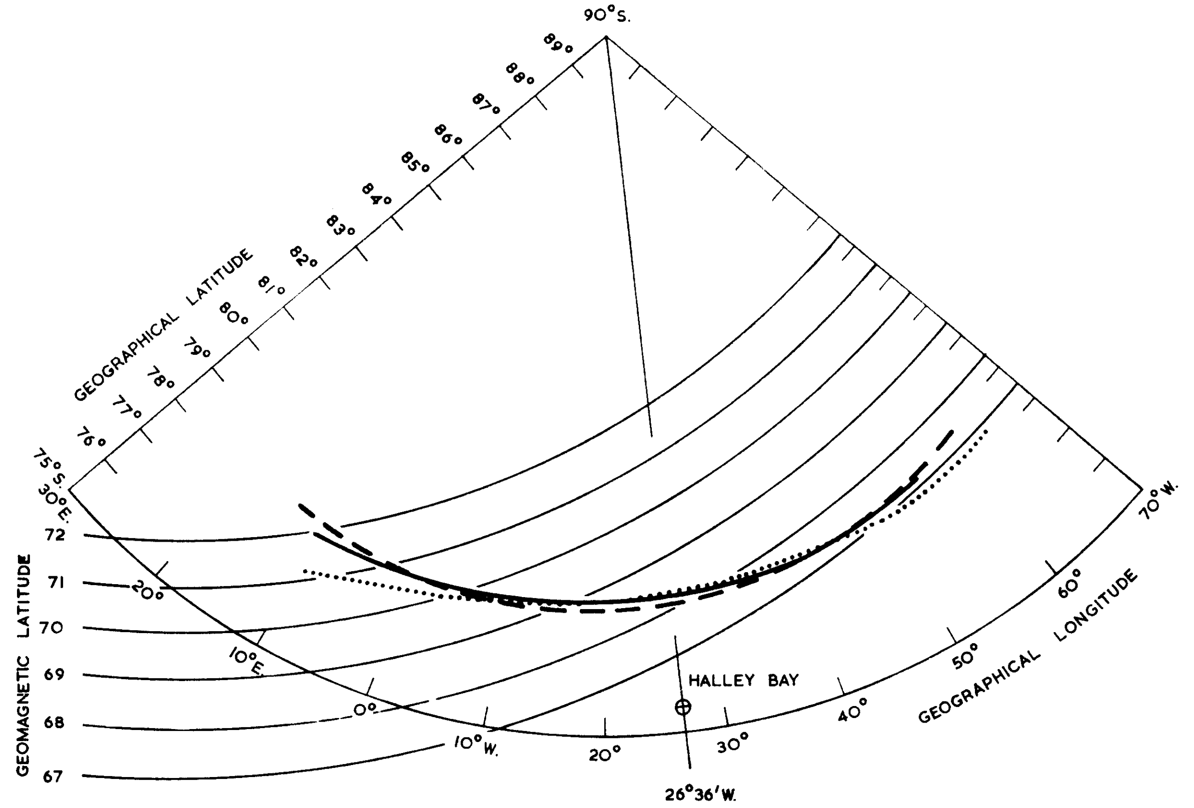


FIGURE 6

The position of the echoing region compared with the specular contours and with lines of geomagnetic latitude:——— echoing region (for a height of 100 km.); . . . . 110 km. specular contour for a magnetic field parallel to that at the surface (Vestine and others (1947*b*), fitted to the Halley Bay 1957 values); — — — — — 100 km. specular contour for field directions computed for a height of 100 km. (Vestine and others (1947*a*), no correction). (After Harrison, 1962.)

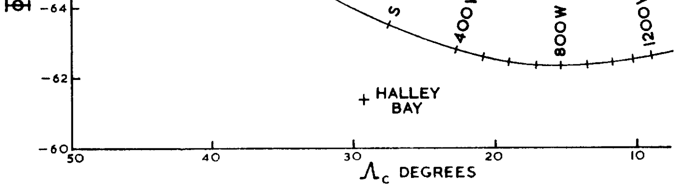


FIGURE 7

The echoing region in corrected geomagnetic latitude, Φ_c, and longitude, Λ_c (Hakura, 1965). The slant ranges of various parts of the region are indicated in kilometres.

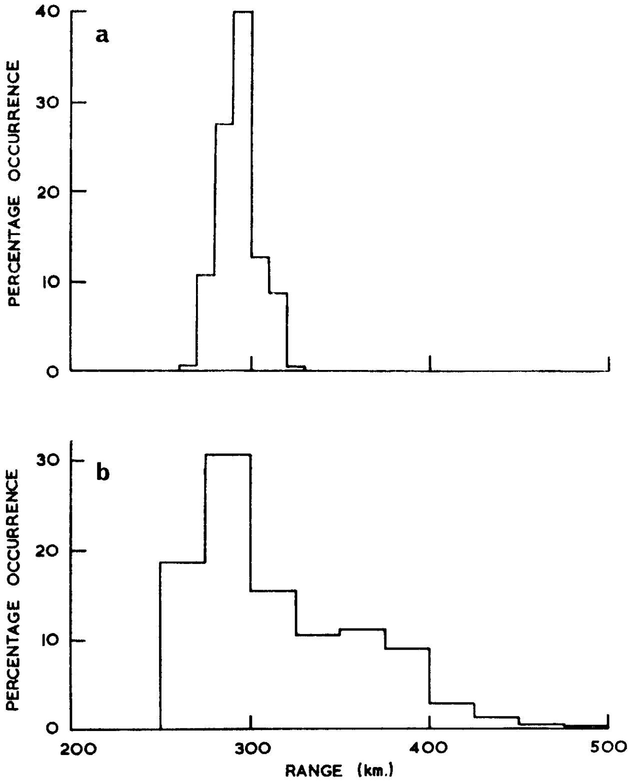


FIGURE 8

Range distributions of radio aurorae in that part of the echoing region closest to Halley Bay.
a. I.G.Y. data (after Harrison, 1962).
b. I.Q.S.Y. data.

the echoing region had occurred between the I.G.Y. and I.Q.S.Y., and it is reasonable to assume that the whole of the echoing region had remained substantially the same. The position of the echoing region as determined by Harrison has therefore been used when determining the corrected geomagnetic latitudes of radio aurorae.

IV. TEMPORAL VARIATIONS IN RADIO-AURORAL ACTIVITY

1. *Diurnal variations in the occurrence of radio aurorae*

The diurnal variations of radio aurorae at Halley Bay during the I.Q.S.Y. are shown in Fig. 9. Here the amplitude indices, as given by the four-figure indices described on p. 9, have been summed separately for echoes obtained from the east and west limbs of the echoing region. The two graphs are thus weighted by the echo intensities and by the diversity of echo type. No correction has been applied for loss of observing time which was low, particularly during the period when radio aurorae were frequently observed, as shown in Fig. 4. No observations were made on the south-west aerial during January 1966 but the resulting correction required to the west limb diurnal variation curve is less than 3 per cent.

The diurnal variation curves are bimodal, each showing a deep minimum near geomagnetic noon and a secondary minimum near geomagnetic midnight, in common with all observations from still lower geomagnetic latitudes (e.g. Kaiser and Bullough, 1955; Watkins, 1961; Leonard, 1962; Sprenger and Glöde, 1964; Unwin, 1966*a*). The curves differ, however, from some observed at higher geomagnetic latitudes which had only a single maximum (e.g. Harang and Tröim, 1961; Leonard, 1962) or as many as three maxima (e.g. Birfeld, 1960; Leadabrand, 1961; Egeland and Ericsson, 1962). These related observations are discussed at length on p. 29–32.

The diurnal variations found at Halley Bay during the winter and spring of 1957 (Harrison, 1962) are

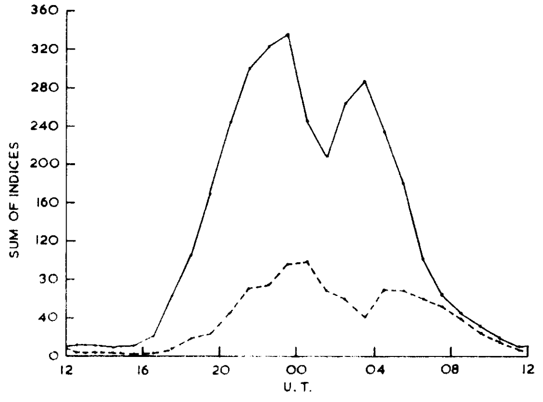


FIGURE 9

The diurnal variation in radio-auroral activity on the two limbs of the echoing region for the period 11 April 1965–20 January 1966.

——— East limb; – – – – – – West limb.

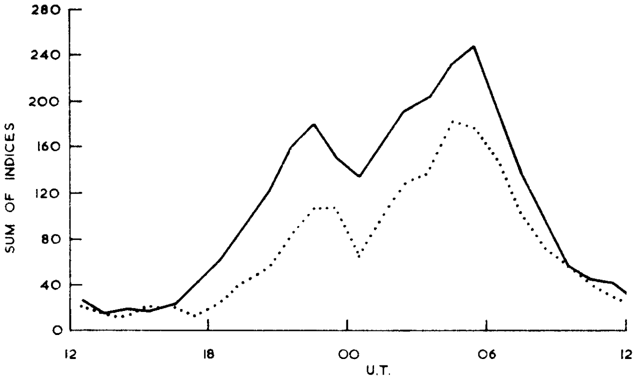


FIGURE 10

As Fig. 9 but for the period 20 May 1957–31 October 1957. (After Harrison, 1962.)

shown for comparison in Fig. 10. Striking differences are apparent between the two sets of graphs. In particular:

i. The proportion of west limb to east limb activity in the I.Q.S.Y. was much lower than in the I.G.Y.
ii. The peaks of activity in the I.Q.S.Y. lay closer to local geomagnetic midnight than in the I.G.Y.
iii. In the I.G.Y. the morning peak of activity predominated over the evening peak, whereas in the I.Q.S.Y. the evening peak was dominant.
iv. In the I.Q.S.Y. there was a marked difference in the times of the "midnight" minima on the two limbs, the difference being largely absent in the I.G.Y.

Possible explanations of these differences are discussed on p. 19–23.

It is interesting to note that, despite the large differences between the two sets of results, both in the I.G.Y. and I.Q.S.Y. the activity became more equally distributed between the two limbs in the late morning, 08–12 hr. U.T., a feature noted by Harrison (1962).

It is not possible to compare directly the observations made using the south aerial with those made using the other two aerials. At the echoing region's point of closest approach to Halley Bay the reflection geometry is greatly simplified and, whatever the character of the ionization present, aspect sensitivity limits the observed ionization to a very narrow depth in range. In consequence, that ionization observed

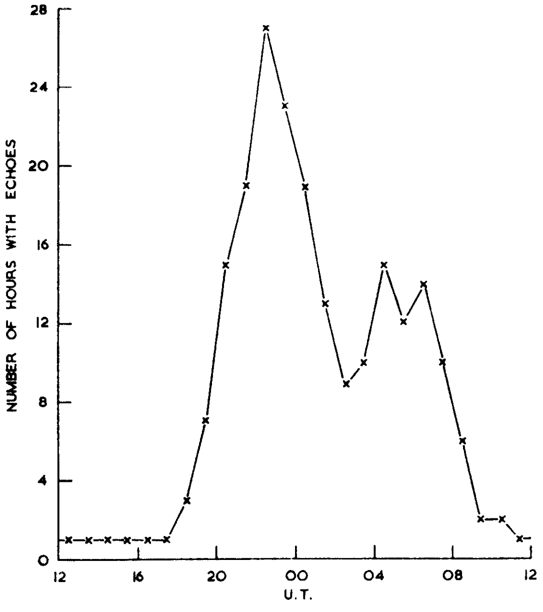


FIGURE 11

Diurnal variation in the number of hours in which radio aurorae were observed using the south rhombic aerial.

with the south aerial gave predominantly discrete echoes. The point of closest approach of the echoing region also lay close to the first minimum in the vertical polar diagram of the aerial so that the intensities of the echoes obtained were abnormally low. A diurnal variation curve was derived from those observations by summing the numbers of hours with echoes for each hour U.T. and is shown in Fig. 11. The period covered was the same as in the previous analysis, namely 11 April 1965 through to 20 January 1966.

2. *Diurnal variations of different types of radio aurora*

The diurnal variations of the three types of radio aurora observed on the east and west limbs of the echoing region are presented in Fig. 12. In each 24 min. period the amplitude index assigned to each echo type was the maximum index observed for that type in that interval. The full-line graphs of Fig. 12 are sums of these indices and are thus intensity weighted. The dotted graphs, however, show the numbers of times that radio aurorae of each type occurred in each 24 min. period.

There are marked differences between the diurnal variations of discrete and diffuse radio aurorae on the two limbs. The lower-latitude, west limb observations display a concentration of diffuse echoes in the evening and of discrete echoes in the morning, in common with observations from still lower geomagnetic latitudes (Bullough and Kaiser, 1955; Unwin, 1966*b*). At the higher geomagnetic latitudes surveyed by the south-east aerial the diurnal variations of these two types are much more similar though there is a noticeable tendency for the discrete echoes to be obtained later, on average, than the diffuse echoes. The evening peaks of discrete and diffuse radio aurorae are displaced by approximately 2 hr. In contrast, the time displacement between the morning peaks is slightly less than 1 hr. and the midnight minima occur virtually simultaneously.

The diurnal variations of structured diffuse radio aurorae observed on the two limbs of the echoing region also differ from those of diffuse and discrete radio aurorae, particularly in the case of the west limb observations. These diurnal variations, however, are of the form expected if the structured diffuse echoes are obtained when diffuse and discrete radio aurorae occur simultaneously in the same range interval.

Harrison (1962) did not present corresponding analyses of the I.G.Y. data. Such analyses have been carried out, however, using Harrison's table of radio-auroral indices and the results are shown in Fig. 13, together with the I.Q.S.Y. results derived from the four-figure indices. Both sets of graphs in Fig. 13 were derived by summing the corresponding amplitude indices and are thus weighted by the intensities. The differences between the I.G.Y. and I.Q.S.Y. results noted in connection with Figs. 9 and 10 are clearly

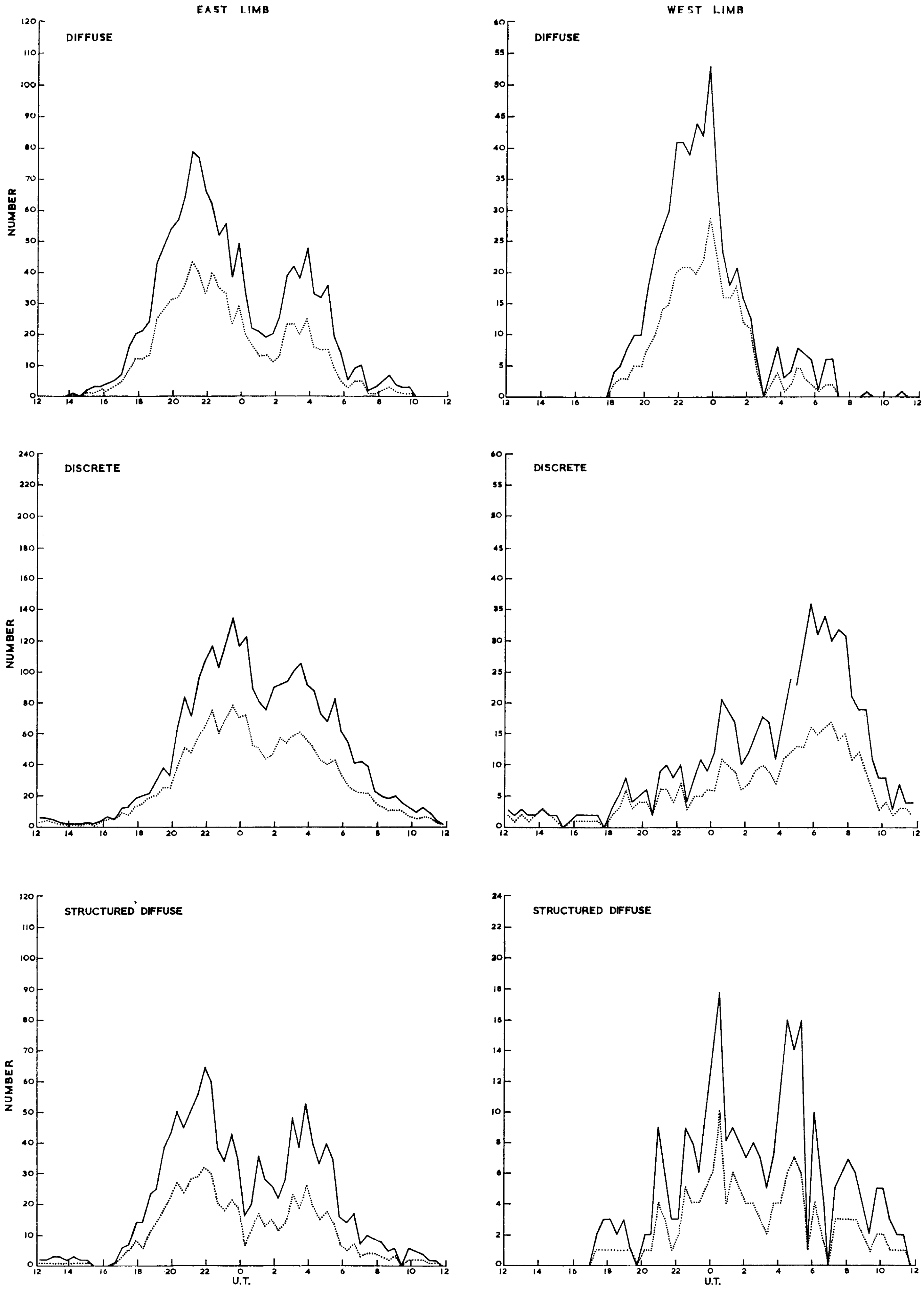


FIGURE 12

Diurnal variations in the occurrence of different types of radio aurora.

.... The number of 24 min. periods with echoes.

———— The sums of the hourly amplitude indices.

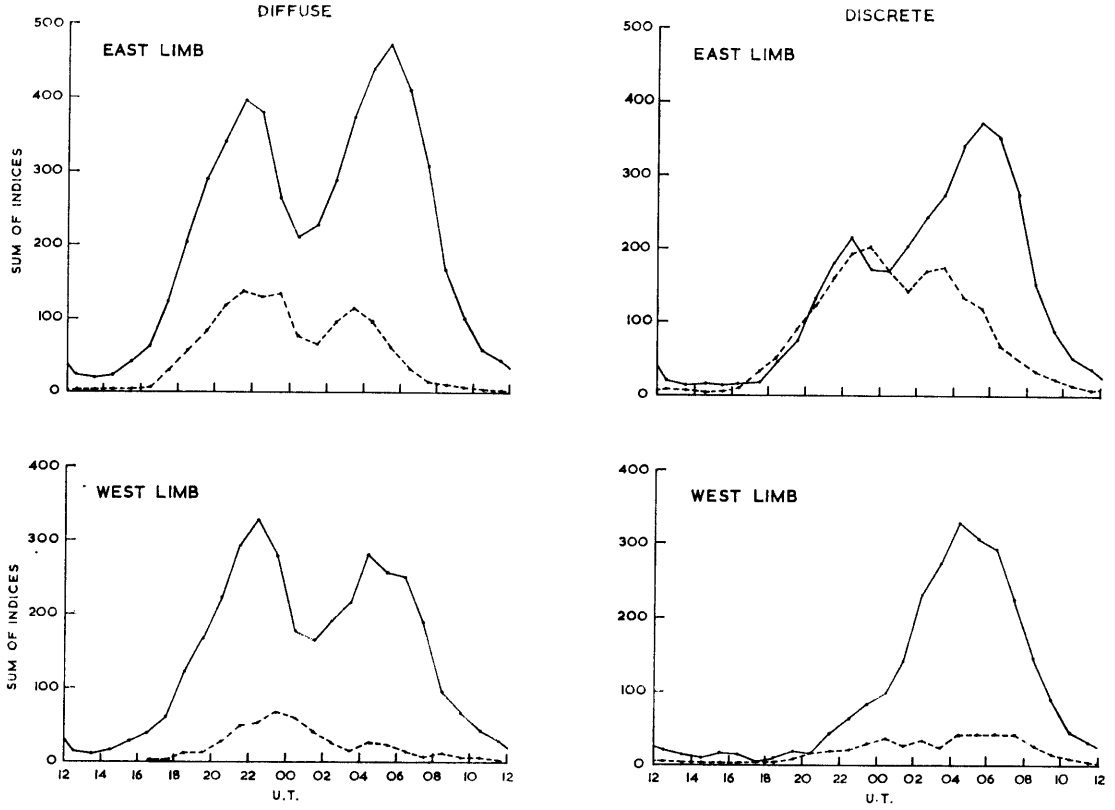


FIGURE 13

Diurnal variations in the occurrence of discrete and diffuse radio aurorae as given by the sums of the hourly amplitude indices for the I.Q.S.Y. (- - - -) and the I.G.Y. (————) periods of observation.

evident in the set of graphs of Fig. 13. In addition, diffuse echoes predominated over discrete echoes in the I.G.Y., whilst in the I.Q.S.Y. there were more discrete echoes than diffuse ones.

3. *Seasonal variations in radio-auroral activity*

Fig. 14 shows the seasonal variation in occurrence of radio aurorae irrespective of type, as represented by the monthly sums of the number of hours in which radio aurorae were observed on the south-east and south rhombics. Where corrections have been applied for loss of observing time, the number of hours added has been indicated by a vertical bar. The large corrections applied in April 1965 and January 1966 to the east limb results arose because operation on the south-east aerial did not commence until 11 April 1965 and ceased on 20 January 1966. No corrections have been applied to the east limb observations throughout the period of operation on the south-east rhombic since the loss of observing time was very small. During periods in which the south rhombic was out of service the west limb observations were used as a check on the likelihood of echoes being observed on the south rhombic, the periods in which echoes were observed on these two aerials being usually coincident. On this basis, no corrections were thought to be worthwhile during the period May to December inclusive.

Both graphs show a peak in activity in September, a commonly observed feature. No peak in activity was found in March. Results for that period, however, were restricted to the low-sensitivity south rhombic observations. The prominent peak of activity in June results largely from the prolonged activity of 15–18 June, the most outstanding event in a year of predominantly weak geomagnetic activity. Comparison of the results obtained on the two aerials indicates that the high levels of activity recorded in July and August on the east limb were of prolonged but relatively weak activity which rarely extended to the lower geomagnetic latitude of the specular contour at the point surveyed by the south rhombic.

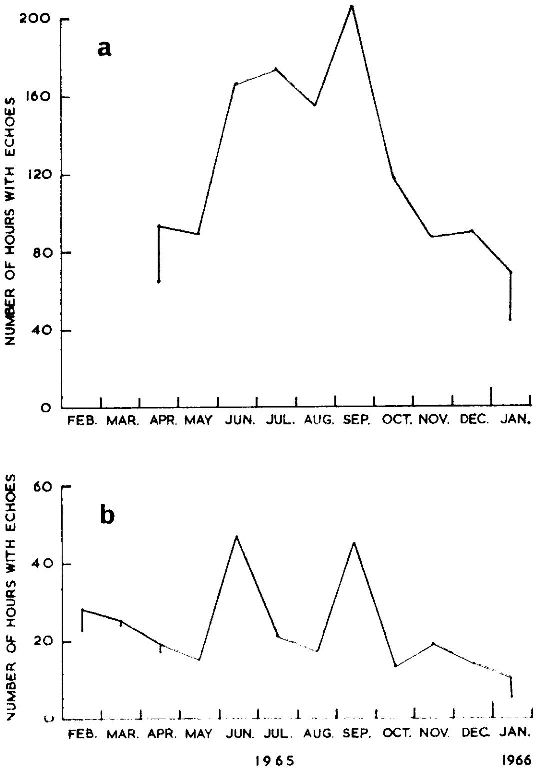


FIGURE 14

Seasonal variations in the occurrence of radio aurorae observed with (a) the south-east antenna and (b) the south antenna. The vertical bars indicate corrections for loss of observing time.

The set of graphs in Fig. 15 shows the diurnal variations of diffuse and discrete radio aurorae for both limbs during three periods, each of 3 months' duration. Echoes of the structured diffuse type were added to both the discrete and diffuse types in deriving the amplitude indices and the graphs in Fig. 15 are sums of these indices.

The seasonal variations of the diffuse and discrete radio aurorae have also been derived in a form independent of the level of magnetic disturbance. Using the results from the whole period during which the south-east rhombic was in service a 3 hourly index of occurrence was derived for both types of radio aurora, this being the number of hours in each 3 hr. period which contained radio echoes. The probability of observing such echoes during 1 hr. was derived for each 3 hr. period of the day and for each level of K_p index. Considering the interval 18–06 hr. U.T. only, the occurrences of the two types of radio aurora were predicted for each month from the observed probabilities and the distribution of K_p indices during the month. The ratios of observed to predicted occurrences are shown in Fig. 16 for both echo types. The numbers of observed events, of each type, used in the derivation of these results are listed above the graphs. The different behaviour exhibited by the two types of echo is considered to be significant. For a given level of geomagnetic activity, echoes of the diffuse type are more likely to be obtained in the spring months than in summer or winter, whilst discrete echoes are more likely to be obtained in winter and early spring, with a minimum in the summer months. The skew nature of the curve for diffuse radio aurorae relative to the periods of low solar zenith angle suggests that the effect does not result from varying illumination of the echoing region. Some such solar control over the occurrence of discrete radio aurorae may, however, be possible.

Sprenger and Glöde (1964) made observations of the radio aurora at a corrected geomagnetic latitude of about 56° N. and found that a given level of radio-auroral activity occurred at a lower value of K_p in winter than at the equinoxes for which, in turn, the value was lower than in the summer months. No attempt was made by these authors to classify their radio aurorae into different types for the purposes of this analysis. Since discrete radio aurorae were nearly always present when some radio aurora was observed

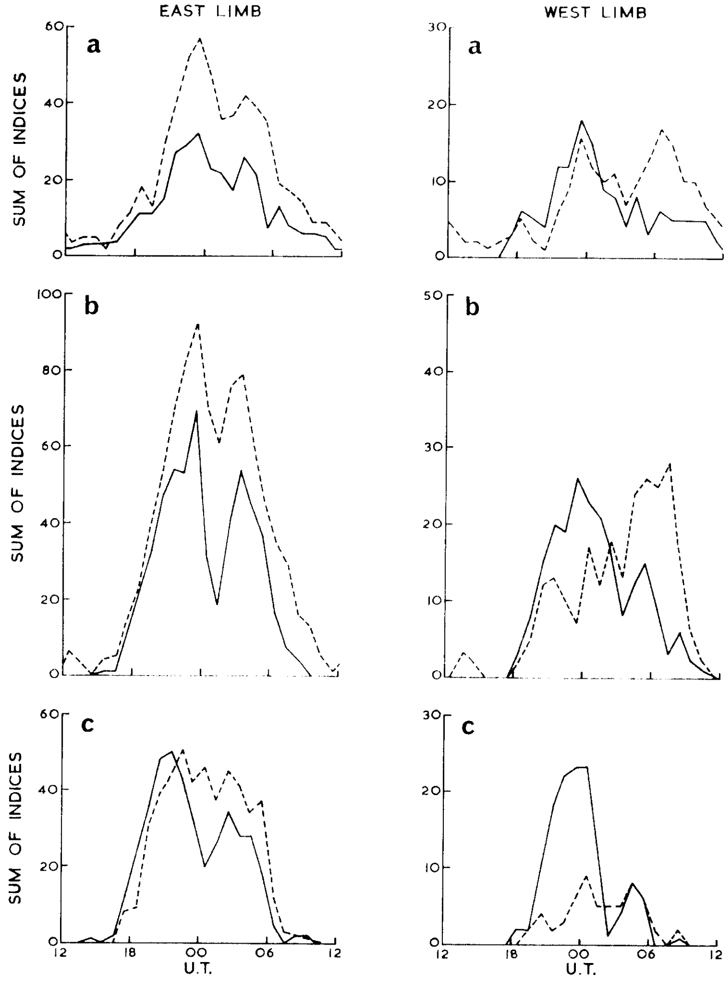


FIGURE 15

Diurnal variations in radio-auroral activity as given by the sums of hourly amplitude indices for the periods: a. April, May and June; b. July, August and September; c. October, November and December.
———— Diffuse radio aurorae.
– – – – – Discrete radio aurorae.

from Halley Bay, the graph for this type in Fig. 16 is most directly comparable with the results of Sprenger and Glöde (1964) and shows very similar variations to these.

Unwin (1966*b*) analysed his observations of the radio aurora from Bluff, New Zealand, during the I.G.Y. in a similar way to that employed in obtaining Fig. 16. Unwin's results would be expected to be very similar to those obtained at Halley Bay, since the range of corrected geomagnetic latitudes covered by the echoing region observable from Bluff is 58–66° S. and overlaps the echoing region observed from Halley Bay to a large extent. Unwin used the local magnetic K index in comparing the seasonal variations in the occurrence of his four types of radio aurora: short discrete (B_2), long discrete (B_3), diffuse (B_1) and diffuse with structure (now also B_1). For all echo types there was a pronounced semi-annual fluctuation with peaks at the equinoxes. Unwin repeated his analysis for diffuse radio aurorae using K_p as the index of magnetic disturbance and in this case found a tendency towards an annual variation with maximum probability of occurrence in the period November–January, at which time there was a sharp minimum in the occurrence of both diffuse and discrete radio aurorae observed from Halley Bay. Whilst the discrepancies between the two sets of observations may be due to the fact that these were made at different epochs of the solar cycle, this is thought to be unlikely since the conclusion is reached on p. 23 that the behaviour of the radio aurora varies very little throughout the solar cycle when corrections are applied for changes in the level of magnetic

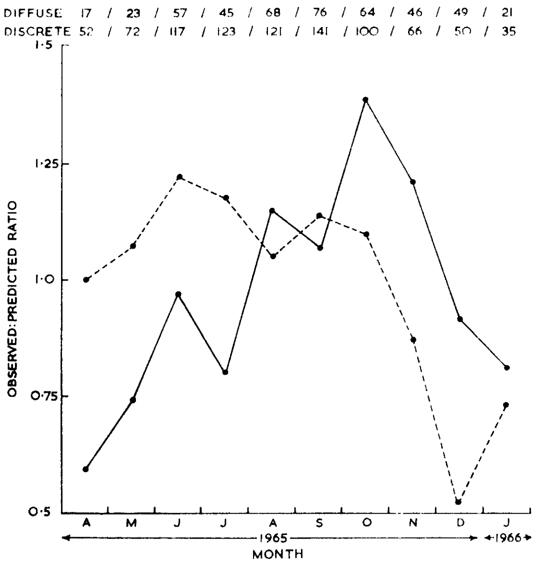


FIGURE 16

Seasonal variation in the ratio of the observed occurrence of radio aurorae to that predicted from the diurnal variation of K_p.
———— Diffuse radio aurorae.
– – – – – Discrete radio aurorae.

disturbance. The discrepancies may, however, be due to the use of radars of different sensitivities coupled with seasonal variations in the intensities of the radio aurorae.

4. *Recurrence tendencies in the radio aurora*

It has long been established that similar levels of geomagnetic activity show a tendency to recur with a period of approximately 27 days, this tendency being associated with the rotational period of the Sun (Broun, 1858; Chree and Stagg, 1927). The results obtained at Halley Bay during the I.G.Y. (Harrison, 1962) and in 1962 (personal communication from J. S. Marsden) show clear evidence of a 27 day recurrence tendency in the occurrence or radio aurorae. A search was made for this effect in the I.Q.S.Y. results.

The auto-correlation coefficient, r, was computed for varying step lengths in the range 0–60 days using a standard programme on the University of Sheffield Mercury computer. The calculations were based on (a) the daily number of 1 hr. periods with radio-auroral echoes, (b) the daily sums of hourly amplitude indices and (c) the daily sums of K_p indices, as daily indices of activity. The periods covered by the indices are relatively short, being 11 April 1965 to 20 January 1966 (285 days) for the radio-echo results (a) and (b), and 20 January 1965 to 20 January 1966 (366 days) for the K_p index sums (c). Fig. 17 shows the correlation curves obtained for each set of observations.

Inspection of the correlation curves suggests that, due to persistence of periods of disturbance or calm for several days, association between adjacent days is important over a period of approximately 5 days giving 57 independent points for curves (a) and (b) and 73 independent points for curve (c). For all three curves, the probability of any of the observed features occurring by chance is greater than 10 per cent (Fisher and Yates, 1948). None of the features is therefore of statistical significance. If a 27 day recurrence tendency in radio-auroral activity had not previously been found, the results quoted here give no justification for believing that such an association exists.

Despite the short interval covered by the observations, the results are contrary to expectation. Marsden's results for 1962, a comparably short period of observation, show very clear indications of a 27 day recurrence tendency. It has long been known that intense geomagnetic disturbances are not associated with the 27 day recurrence tendency, such recurrences being a feature of the weaker periods of geomagnetic activity (Greaves and Newton, 1928, 1929; Allen, 1944). A more prominent peak in the correlation curve at 27 days than is observed would therefore be expected for the I.Q.S.Y. results.

The relative amplitudes of the correlation curves (a) and (b) at 27 days are compatible with the result

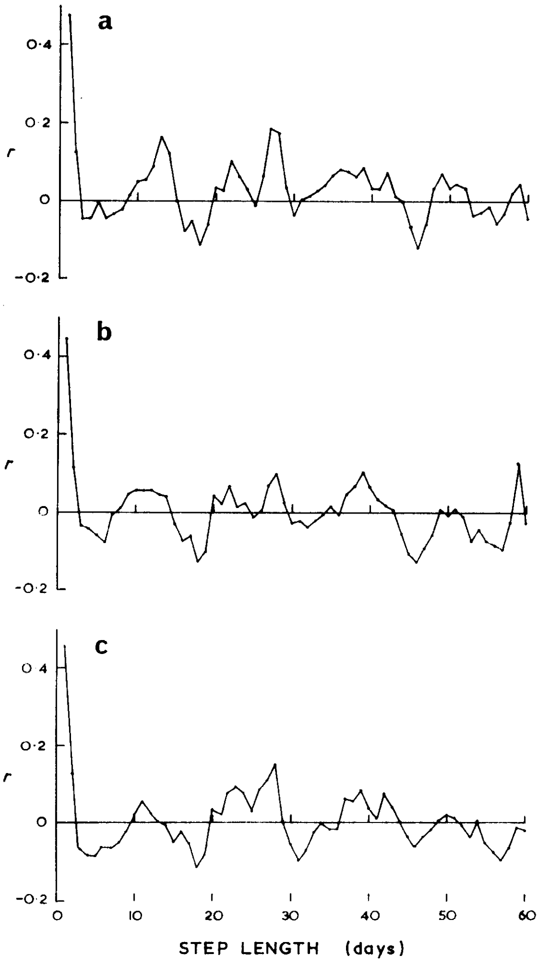


FIGURE 17

The auto-correlation function, *r*, computed for:

a. The daily number of 1 hr. periods with echoes (11 April 1965–20 January 1966).

b. The daily sums of hourly amplitude indices (11 April 1965–20 January 1966).

c. The daily sums of K_p indices (20 January 1965–20 January 1966).

quoted above, that weak rather than very intense periods of geomagnetic disturbance show a tendency to recur at intervals of 27 days. The form of curve (a), which is based on the number of hours with echoes, is determined largely by the higher-latitude, east limb observations. This curve therefore gives much greater weight to periods of weak activity than does curve (b), which is based on the sums of hourly amplitude indices, and it is in curve (a) that the peak at 27 days is most prominent.

V. RELATION OF RADIO AURORAE TO GEOMAGNETIC DISTURBANCE

MANY research programmes at sub-auroral latitudes have demonstrated that the probability of occurrence of radio aurora increases with increase of geomagnetic disturbance (e.g. Bullough and others, 1957; Watkins, 1961). Harrison (1962) demonstrated that the radio-auroral activity observed at Halley Bay during the I.G.Y. followed closely the changes in world-wide magnetic activity over a wide range of conditions. In Fig. 18 the daily numbers of hours with echoes from the radio aurora are compared with the daily sums of both the planetary and local magnetic K indices. The product moment cross-correlation coefficients computed between the daily numbers of hours with echoes and the daily sums of K_p and local

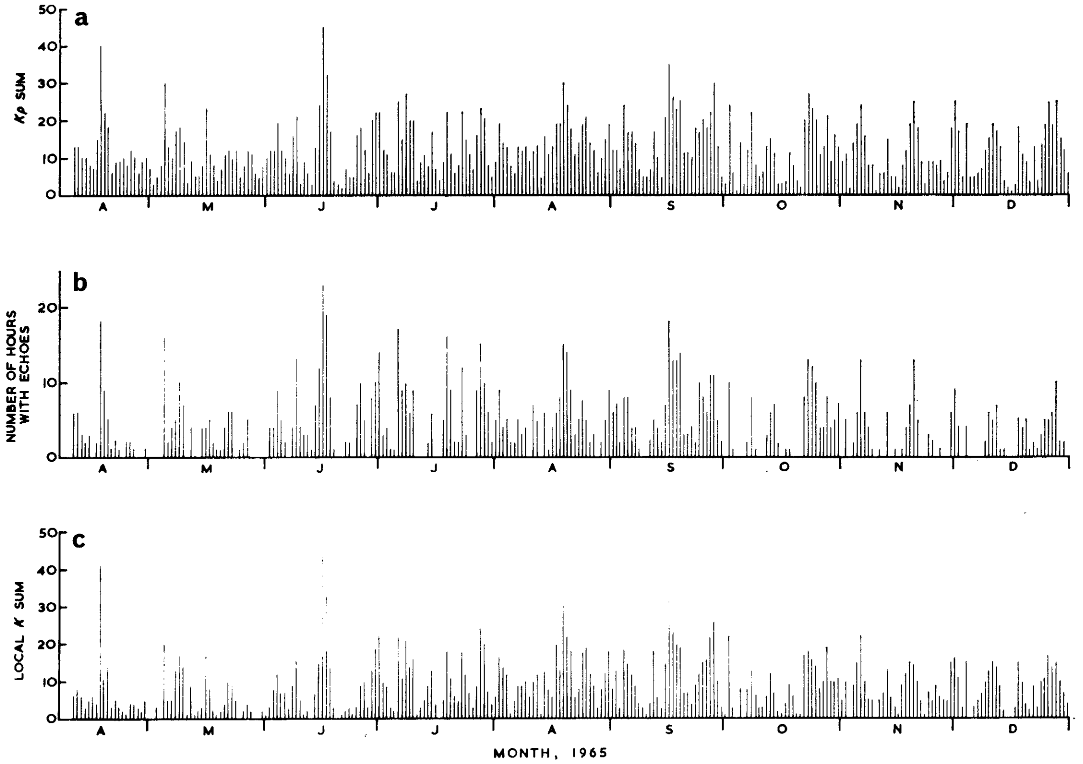


FIGURE 18

Comparison of (b) the number of 1 hr. periods per day with radio-auroral echoes with the daily sums of (a) the planetary magnetic index, K_p, and (c) the local magnetic index, K.

K, in turn, were found to be +0·875 and +0·870, respectively. (The difference between the values of the two coefficients is not statistically significant.) The evidence for a close association between the two phenomena is therefore very clear. The histogram in Fig. 19 shows how the probability of observing radio aurorae increased during the I.Q.S.Y. as the magnetic activity, represented by K_p, increased.

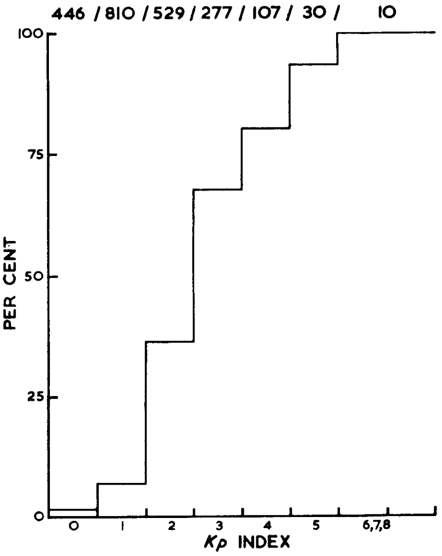


FIGURE 19

The proportion of 3 hr. periods with radio-auroral echoes at each level of magnetic disturbance. Sample sizes are given at the top of the diagram (11 April 1965–20 January 1966).

The set of graphs in Fig. 20 shows, for different levels of K_p, the probability of occurrence of radio aurora in each 3 hr. period of the day. For moderate levels of magnetic disturbance, $K_p = 3$ and 4, the diurnal variation curves are markedly symmetrical about the time of the secondary minimum. For lower values of K_p, however, the curves are clearly asymmetrical, though the variations for $K_p = 0$ are not statistically significant.

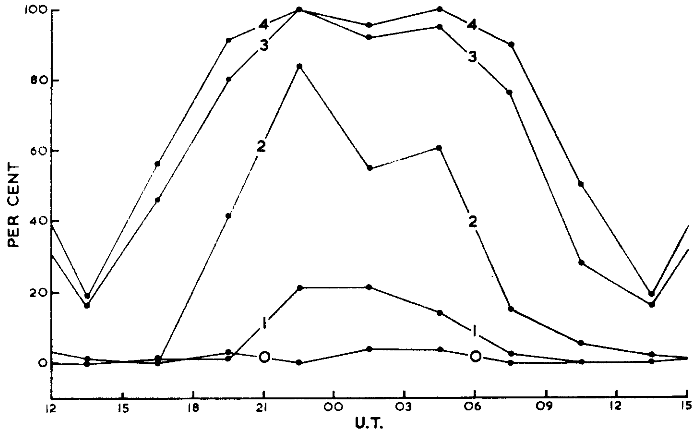


FIGURE 20

The diurnal variation in the probability of observing radio aurorae during each 3 hr. period (U.T.) for different values of K_p, using data from 11 April 1965 to 20 January 1966.

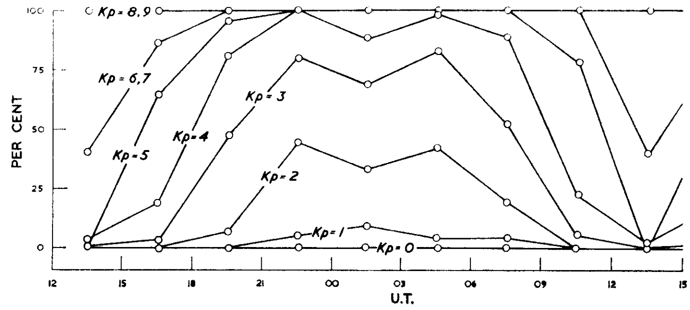


FIGURE 21

As Fig. 20 but for the period January–June 1958 (after Harrison, 1962).

As an aid to comparison, similar results derived by Harrison (1962) from his observations at Halley Bay during the I.G.Y. are reproduced here as Fig. 21. The differences between the two sets of graphs are striking. The I.Q.S.Y. results, as already noted, are markedly asymmetrical about the time of the secondary minimum for low K_p values, whilst the I.G.Y. results are symmetrical at all levels of geomagnetic disturbance.

The graph for $K_p = 2$ (Fig. 20) bears the main features of the diurnal variation in occurrence of radio aurorae as observed at Halley Bay during the I.Q.S.Y. Fig. 22 reveals the parts played by radio aurorae observed at different levels of magnetic activity in determining the form of the diurnal variation curve. With increasing K_p value the probability of observing radio aurorae increased rapidly. As K_p increased above 1, however, the probability of each value of K_p occurring decreased as shown at the top of Fig. 19. Consequently, it was those radio aurorae which occurred at $K_p = 2$ and 3 that played the dominant role in determining the shape of the diurnal variation curve.

The intensities of the echoes from the radio aurora also proved to be dependent upon U.T. and the level of magnetic disturbance is shown in Fig. 23, where the results for discrete and diffuse echoes are treated separately. It must be noted that these results, which are derived from the hourly amplitude indices for the whole period of observation, are the mean values of the maximum hourly amplitudes and not the mean

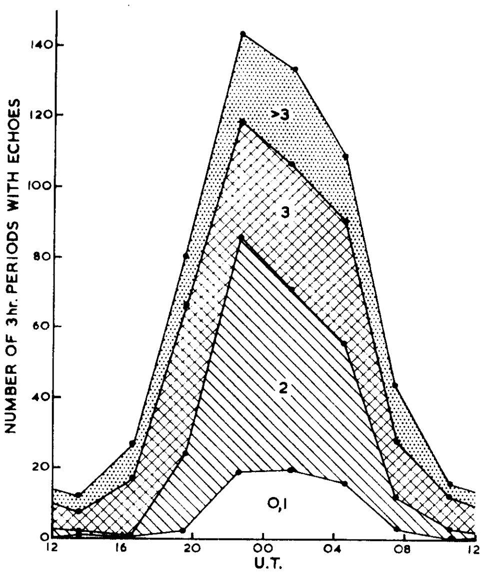


FIGURE 22

The parts played by radio aurorae occurring at each level of K_p in determining the shape of the diurnal variation curve.

amplitudes of all echoes observed. All graphs display a greater mean amplitude index in the morning than in the evening. Whilst the increase in the mean amplitude of discrete echoes is relatively smooth, there is a deep minimum in the mean amplitude of diffuse echoes around local midnight for moderate levels of magnetic disturbance, K_p = 3 and 4.

Following the improvement of the receiver noise figure and the use of aerials of higher gain, the overall

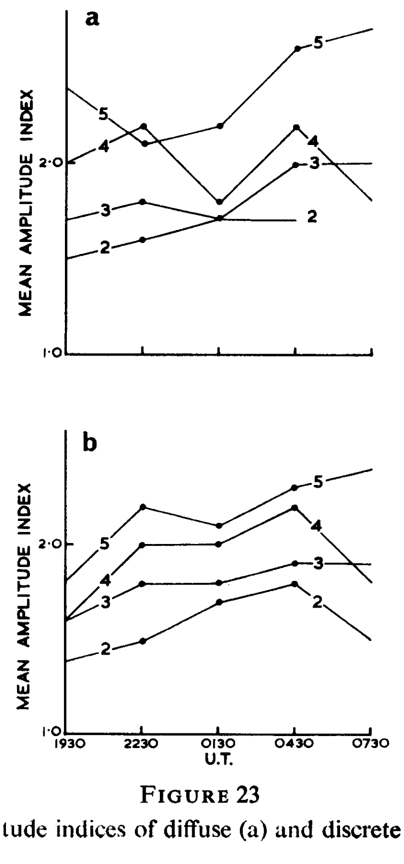


FIGURE 23

Diurnal variations in the mean amplitude indices of diffuse (a) and discrete (b) echoes for different values of K_p.

sensitivity of the equipment during the I.Q.S.Y. was greater than during the I.G.Y. The weak echoes observed at any K_p value during the I.Q.S.Y. would therefore not have been recorded by the less sensitive equipment used during the I.G.Y. At moderate levels of magnetic activity, $K_p=3$ and 4, at which echoes are likely to have reached sufficient intensity to be recorded by both equipments, the I.G.Y. and I.Q.S.Y. results are closely similar in form. At lower K_p values, $K_p=1$ and 2, the occurrence in the evening of a high proportion of echoes which are relatively weak, as shown in Fig. 23, could explain the absence in the I.G.Y. results of the asymmetry evident in the I.Q.S.Y. results. As already demonstrated, radio aurorae occurring when $K_p=2$ played a very important part in determining the exact forms of the diurnal variation curves during the I.Q.S.Y. It thus seems that the differences between the I.G.Y. and I.Q.S.Y. diurnal variation curves were produced by the use of more sensitive equipment during the I.Q.S.Y. and the decrease in geomagnetic activity between the two periods of observation.

It was noted on p. 11–12 that the proportion of west to east limb activity during the I.Q.S.Y. was much lower than during the I.G.Y. Due to the increased sensitivity of the radar used during the I.Q.S.Y. and to the scarcity of periods of high magnetic disturbance, relative to the conditions prevailing during the I.G.Y., most of the echoes observed were associated with periods of relatively weak magnetic disturbance, during which the radio-auroral zone would be expected to show little tendency to extend to the lower geomagnetic latitudes surveyed by the south-west aerial. Evidence for the existence of a radio-auroral zone, which exhibits the behaviour assumed here, is discussed at length on p. 23–32. During the I.G.Y. most of the radio aurorae observed were associated with the relatively high levels of magnetic disturbance, during which the radio-auroral zone would be expected to extend equatorwards, into and beyond the range of geomagnetic latitudes covered by the west limb of the specular contour.

The results presented in Fig. 20, though relatively crude, are in general agreement with the conclusions drawn by Unwin (1966*a*) from a similar analysis of observations made at Bluff, New Zealand, during the I.G.Y. He concluded that the pre-midnight peak in the occurrence of radio aurorae appears earlier in the evening and the post-midnight peak later in the morning as the level of magnetic activity increases. As a result of the increased association of radio-auroral echoes with periods of weak magnetic disturbance during the I.Q.S.Y., the evening peak in occurrence would therefore be expected to appear later, and the morning peak earlier, than during the I.G.Y., as observed.

The differences between the times of the secondary minima in the diurnal variation curves of radio aurorae in the I.G.Y. and I.Q.S.Y. may also be products of the relatively quiet magnetic conditions and improved equipment sensitivity during the I.Q.S.Y. The observation of a greater number of radio aurorae which are associated with the evening peak in activity rather than with the morning peak automatically shifts the time of the minimum towards the morning hours and could easily account for changes of the magnitude observed.

It is thus possible to explain qualitatively the observed differences in the latitudinal distributions and diurnal variations of the radio aurora during the two periods of observation. In doing so, it has not been necessary to assume that any changes occurred in the world-wide distribution of radio aurorae throughout the solar cycle other than those average changes which resulted from variations in the mean level of magnetic disturbance. A study of the behaviour of the visual auroral oval in the I.G.Y. and I.Q.S.Y. by Feldstein and Starkov (1968) suggested that any solar cycle variations in the distribution of radio aurorae should be small. The centre line of the visual auroral oval near midnight in the I.Q.S.Y. was only 1° poleward of its position at the same time of day and at the same level of magnetic disturbance during the I.G.Y.

VI. MORPHOLOGY OF THE RADIO AURORA

1. *Introduction*

At most sites used in the study of the radio aurora the specular condition for reflection from field-aligned ionization so limited the range of geomagnetic latitudes in which the radio aurora could be observed that single-station studies of its distribution in latitude were rendered impossible. Before the I.G.Y. studies of the radio aurora were carried out from one station at a time and with radars of widely differing characteristics, defeating all attempts to connect the observations into a synoptic pattern. On p. 19–23 the influence of equipment sensitivity upon observations, even when made from the same station and at the same radio frequency, has been amply demonstrated.

The first major attempt to obtain information on the latitudinal distribution of the radio aurora was made by a team of research workers in Alaska during the I.G.Y. (Leonard, 1962). A chain of five similar 40 MHz radars was used, these being distributed approximately along a magnetic meridian to observe radio aurorae within the range of geomagnetic latitudes 60–80° N. which includes the visual auroral zone. The results indicated an apparent radio-auroral zone with its maximum at geomagnetic latitude 67° N. The zone was observed to spread equatorwards at times of increased magnetic disturbance.

Radio aurorae may be observed within a considerable range of geomagnetic latitudes from Bluff, New Zealand, and Gadsden (1959*a*) found from observations made at that site on a frequency of 55 MHz during the I.G.Y. that the radio aurora appeared further out from the South Polar region as the local magnetic K index increased. The K index used in this instance was derived from magnetic observations at Macquarie Island, a site very close to the echoing region. Since the probability of observing radio aurorae was dependent on the time of observation, Gadsden concluded that the observations suggested the existence of a radio-auroral zone which might be eccentric about the geographical pole.

Bates (1966) determined the position of the equatorwards boundary of the scattering region in geomagnetic latitude and time, and found that this was eccentric with respect to the geomagnetic pole, and agreed well with the position of the oval of visual aurorae. The radio aurora was present in this region practically continuously, day and night.

A number of authors have noted the presence of spiral patterns in the distribution of radio aurorae (Egeland and others, 1962; Unwin, 1966*a*, *b*). These spirals have been derived by plotting the times of maximum radio-auroral activity in geomagnetic latitude and time using the observations from a large number of stations. Unwin (1966*a*) found three spirals of maximum radio-auroral activity. He has named these the E (evening), N (night) and M (morning) spirals, and has found them to agree well with the spirals of maximum magnetic agitation given by Feldstein (1963). Unwin (1966*b*) showed that diffuse radio aurorae are predominantly associated with the E spiral, whilst the short and long discrete radio aurorae are associated with the N and M spirals, respectively.

Observations of the radio aurora inside the polar cap will be discussed on p. 40–41.

2. *Analysis of the I.Q.S.Y. observations at Halley Bay*

The site at Halley Bay has been found to be particularly suitable for a study of the latitude dependence of the radio aurora. There are two reasons for this. First, the station proved to be situated in close proximity to the radio-auroral zone, so that, even during the I.Q.S.Y., observations of the radio aurora were relatively frequent. Secondly, as mentioned earlier, the echoing region determined by the condition of specular reflection from field-aligned ionization at a height of 110 km. covers the unusually large range of corrected geomagnetic latitudes 62·4–68° S.

The K_p index of geomagnetic activity has been used throughout the following analysis. There are two main reasons why this index was chosen, rather than the local K index. First, Halley Bay, although being by far the nearest station, is situated at a considerable distance from the echoing region. Even at its point of closest approach this is approximately 300 km. from the station, and most radio aurorae were observed at still greater ranges. At this location then, where ionospheric conditions vary rapidly with position, there is no obvious reason why the K index derived from magnetic observations at Halley Bay should be the more applicable of the two. Secondly, since the aim of the analysis was to study the behaviour of the radio-auroral zone as a whole, K_p would seem to be the relevant magnetic index.

Some support is given to the above procedure by the suggestion of Piddington (1967) that the area of the auroral oval gives an indication of the total magnetic flux in the tail of the magnetosphere. In addition, Speiser (1967) deduced from a theoretical examination of a model of the neutral sheet in the geomagnetic tail that the auroral oval should expand equatorwards as the tail field increases. A high correlation has been found between the tail field magnitudes and K_p (Behannon and Ness, 1966) so that it is this index that should be most closely related to the size and shape of the radio-auroral zone.

Since the K_p index refers to a 3 hr. period of the day, the first step in the analysis was to derive a corresponding index of radio-auroral activity. The index chosen was one-third of the number of hours, during each 3 hr. interval, which contained echoes from the radio aurora. The probability of observing radio aurora, for a particular 3 hr. period and for a particular value of K_p, was then the mean value of the auroral indices for that 3 hr. period and value of K_p. 3 hourly indices of radio-auroral occurrence were derived from observations made within a number of range intervals, each interval covering 100 km. in range. Observations on the east and west limbs of the echoing region were treated separately. Each chosen range interval covers a narrow range of corrected geomagnetic latitudes and the mean latitudes of the selected range intervals are given in Table II. The range distribution of radio aurorae is determined to a large extent by the intersection of the aerial polar diagram with the specular contour at the 110 km. level. The range distributions of the three types of radio aurorae are closely similar when all observations, irrespective of the level of magnetic disturbance, are combined, and the distribution of discrete radio aurorae observed on the east limb is presented in Fig. 24 as a typical example. Range intervals were chosen which included a high proportion of the radio aurorae observed. A radio aurora was said to fall within a particular range interval either if the interval contained more than half of the radio aurora or if this covered more than half of the range interval. The probabilities of occurrence of the diffuse and discrete radio aurorae as functions of Universal Time and K_p value were then determined from the 3 hourly indices and are plotted against corrected geomagnetic latitude in Fig. 25. Only night-side observations have been treated in this way as

TABLE II

MEAN CORRECTED GEOMAGNETIC LATITUDES OF SELECTED RANGE INTERVALS

Range interval (km.)	*Corrected geomagnetic latitude* (°S.)
500–600, west limb	62·5
500–600, east limb	65·1
700–800, east limb	66·1
900–1,000, east limb	67·2

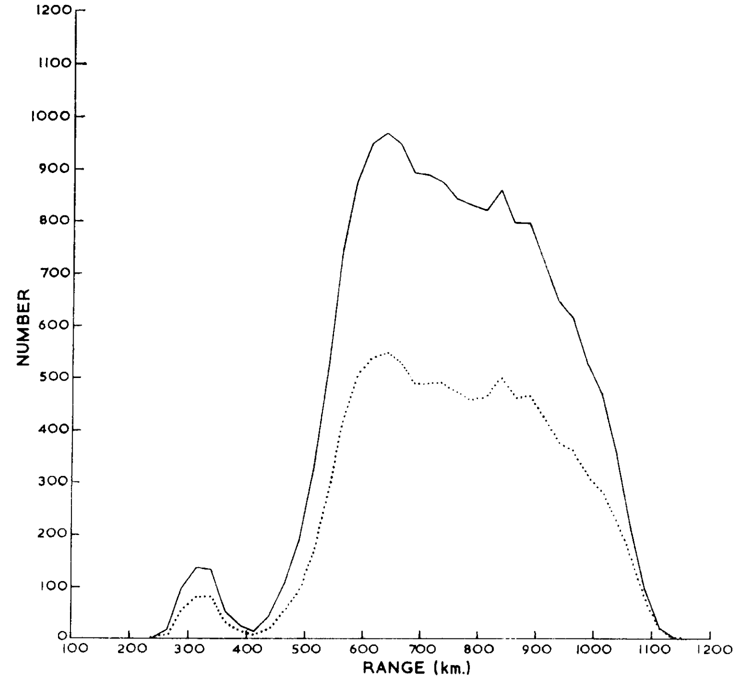
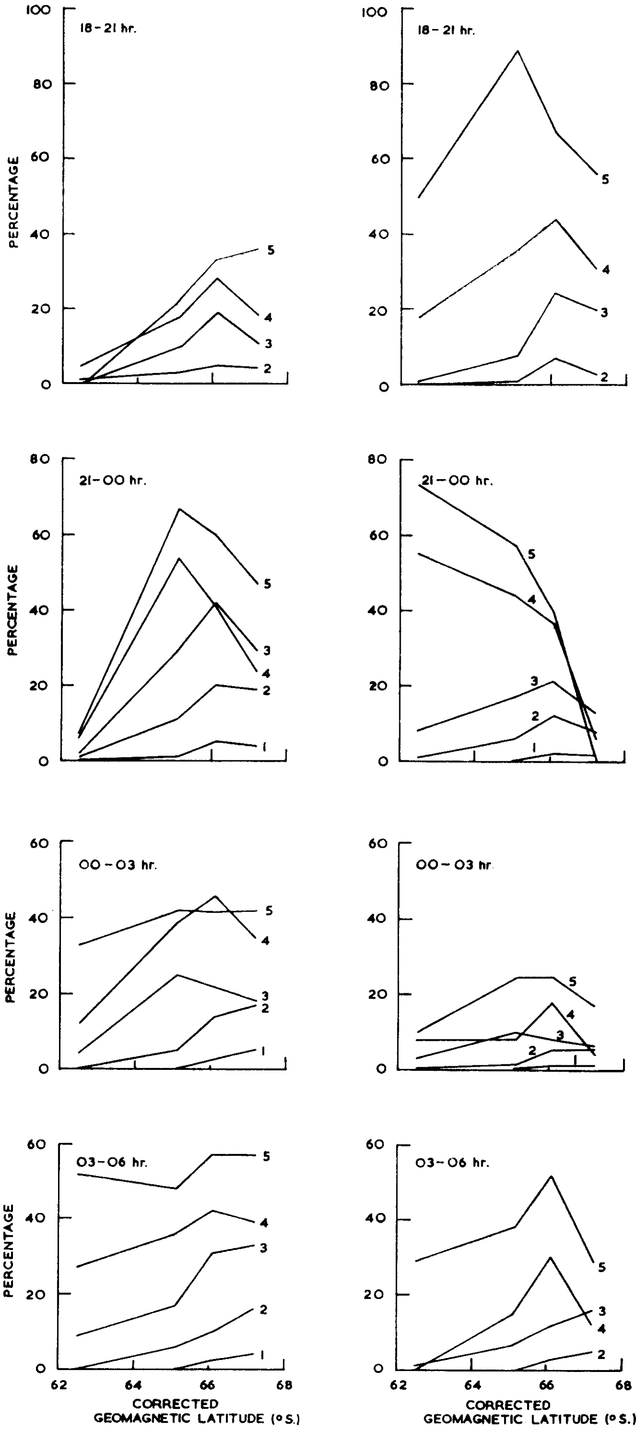


FIGURE 24

The number of discrete radio aurorae observed in each 25 km. range interval on the east limb of the echoing region.
——— Intensity weighted.
.... Occurrence only.



a. DISCRETE

b. DIFFUSE

FIGURE 25

The percentage probability of observing discrete (a) and diffuse (b) radio aurorae as a function of corrected geomagnetic latitude and Universal Time for different values of K_p.

too few radio aurorae were observed on the day-side to give results of statistical significance. Unfortunately, the latitude distributions are slightly modified by the aerial polar diagrams and it has proved impossible to correct for this. However, by examining the sequence of graphs it is easy to study changes in the latitude distributions and to determine the peaks in these latitude distributions with reasonable accuracy. The effects of the polar diagrams upon the two lowest-latitude results may be assumed equal since the range distributions of meteor echoes reveal that the polar diagrams of the south-east and south-west rhombic aerials were closely similar. Some care must be taken in interpreting the distributions, since the variation in geomagnetic latitude along the specular contour is accompanied by a total variation in local geomagnetic time of approximately 2 hr.

Before local midnight there are clearly separate zones of discrete and diffuse radio aurorae with the diffuse zone located equatorwards of the discrete zone. The separation of the two zones increases as the level of magnetic disturbance increases. At low K_p values there is considerable overlap between the two distributions. At moderate levels of magnetic disturbance the peak of the diffuse zone is displaced equatorwards of the echoing region.

After local midnight, the discrete radio aurora shows no tendency to form the pronounced zonal peak displayed by the evening echoes. The discrete activity in the morning is quite widespread and completely overlaps the diffuse zone in the range of observable latitudes. The diffuse zone is restricted to high latitudes at all levels of geomagnetic disturbance and gradually fades as the morning progresses.

It is necessary to consider briefly the latitude distribution of the structured diffuse radio aurorae. Results of a similar analysis for this type, for $K_p=4$, are presented in Fig. 26, the corresponding distributions for the discrete and diffuse types being shown for comparison. If, as has been suggested earlier, the observation of structured diffuse radio aurorae indicates the presence of both discrete and diffuse types, the classification of some radio aurorae as structured diffuse alters the distributions of the other two types. With this in mind, the set of graphs in Fig. 26 is not in disagreement with the above suggestion as to the nature of the structured diffuse radio aurorae. It is to be noted here that separation of the structured diffuse radio aurorae into the component diffuse and discrete types would reduce the differences between the latitude distributions of these two types as deduced from Fig. 25 but differences of the form described above would still exist. Harrison (1962) did not identify structured diffuse radio aurorae as a separate type and his data yield

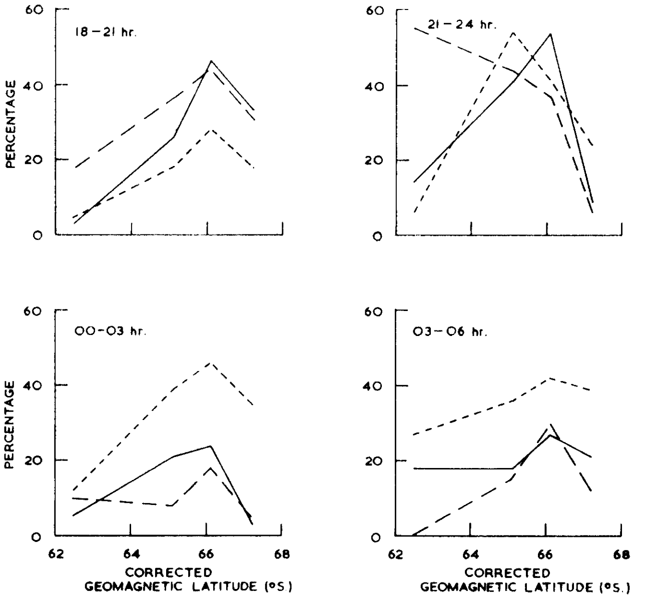


FIGURE 26

The percentage probabilities of observing radio aurorae as a function of corrected geomagnetic latitude and Universal Time for K_p = 4.

— — — Diffuse radio aurorae.
\- - - - Discrete radio aurorae.
——— Structured diffuse radio aurorae.

results in agreement with those of Fig. 25. Harrison did not give range data for his radio aurorae, however, so that in checking the above results it has only been possible to examine their distributions between the east and west limbs of the echoing region.

An increase of geomagnetic activity is known to be accompanied by a displacement of the radio aurora to increasingly lower latitudes. It is thus possible to use the level of geomagnetic activity at which the probability of occurrence of the radio aurora reaches a certain value (for some particular location) to give an indication of the position of the radio aurora, polewards of the observing station, during periods of geomagnetic calm. The intensity of the auroral echoes also increases with the level of geomagnetic activity, however, so that these results cannot provide a measure of the position of the radio aurora under quiescent conditions but give only a general indication of this position.

When the probability of occurrence of the radio aurora, for the diffuse and discrete types separately, was plotted against K_p for each 3 hr. period, a set of graphs of similar form was obtained, an example of which is presented in Fig. 27. From each graph the value of K_p at which the probability of observing radio aurora reached 50 per cent was deduced. In Fig. 28 these results are plotted in polar form together with a graphical estimate of error, the length of the radius vector being proportional to the K_p value. This diagram refers to results from the east limb of the echoing region only, since during the I.Q.S.Y. most of the radio aurorae observed were situated on that limb. The results derived from observations made when the station was close to the noon meridian are of low statistical significance. The K_p values there were obtained by extrapolation, assuming that the curves drawn would belong to the same family as those for night-side observations. The length of the radius vector indicates that at local noon and under quiescent conditions the radio aurora is located at a great distance polewards of the echoing region. The low statistical significance of these results near local noon was due to the very limited occurrence of the radio aurora at that time. This is assumed to be due to the shortage of periods of high geomagnetic disturbance during the I.Q.S.Y. Under these circumstances, the absence of the radio aurora at moderate K_p values is a better indication of the location of the radio aurora than is its presence on the few occasions when the K_p value was high. Too few day-side observations were made of the diffuse radio aurora to give results of statistical significance and these have therefore been quoted only for the night side. When the length of the radius vector is interpreted as an indicator of the distance to the radio-auroral zone, polewards of the echoing region, then the results suggest again the existence of separate zones of diffuse and discrete radio aurora. This diagram could not by itself give conclusive evidence for a difference in the latitudinal distributions of the two radio-auroral types, since similar diagrams would result from different temporal variations of the two types within one zone. However, the results of Fig. 25 have already demonstrated the existence of distinct zones for the two types and it is tempting to use the results of Fig. 28 to extrapolate to the day side the results for the discrete zone. These results suggest that the discrete radio aurora occurs in an oval which is asymmetrical about the Sun–Earth line and much closer to the pole on the noon meridian than on the midnight meridian.

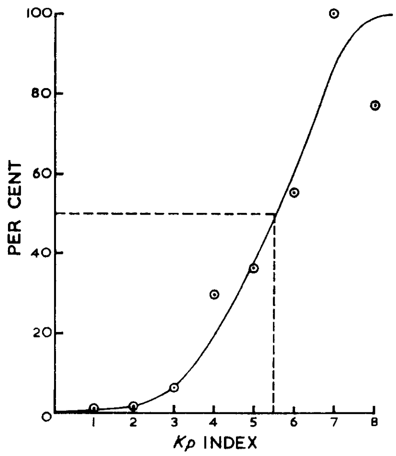


FIGURE 27

The probability of observing discrete radio aurorae on the west limb as a function of K_p for the period 00–03 U.T.

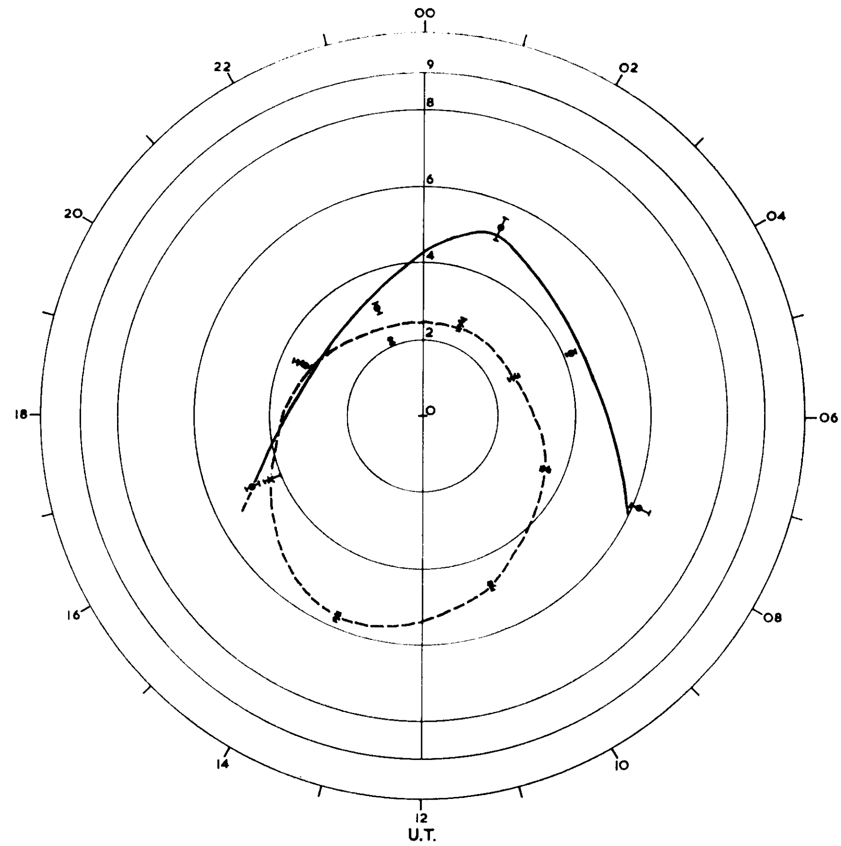


FIGURE 28

The level of K_p at which the probability of observing radio aurorae on the east limb of the echoing region reached 50 per cent during the I.Q.S.Y.

●————● Diffuse radio aurorae.

× ——— × Discrete radio aurorae.

Recourse has been made to the more extensive results obtained at Halley Bay during the I.G.Y. (Harrison, 1962) to examine the day-side behaviour of the diffuse radio aurorae. The results from the I.G.Y. data are presented in Fig. 29 and these were obtained by using the method of analysis described above. These results support those obtained from the I.Q.S.Y. data and suggest that both types of radio aurora occur in ovals which are displaced to opposite sides of the Sun–Earth line. These ovals have already been shown to overlap near geomagnetic midnight and it is possible that they may also overlap near geomagnetic noon.

The differences between the I.G.Y. and I.Q.S.Y. results are believed to be a product of the different equipment sensitivities in the two periods of observation which were discussed on p. 19–23. Following improvement of the receiver noise figure and the use of aerials of higher gain, the equipment used during the I.Q.S.Y. was considerably more sensitive than that used during the I.G.Y.

3. *Comparison with observations at other sites*

The observations which are most directly comparable with the Halley Bay results are those of Unwin (1968). Using data collected during the I.G.Y. on a frequency of 55 MHz from Bluff, New Zealand, Unwin has derived distributions of discrete and diffuse radio aurorae in corrected geomagnetic latitude and time for various ranges of K_p. Unwin's fig. 1 is reproduced here as Fig. 30. The range of corrected geomagnetic latitudes surveyed from Bluff overlaps that covered by the Halley Bay radar to a large extent. The two sets of data presented in Figs. 25 and 30 supplement each other remarkably well considering the difference between the solar-cycle epochs at which they were collected. Particularly noteworthy is the presence in the Bluff data of a peak in the occurrence of diffuse radio aurora for $K_p = 3, 4$ around 21.00 hr. at which time

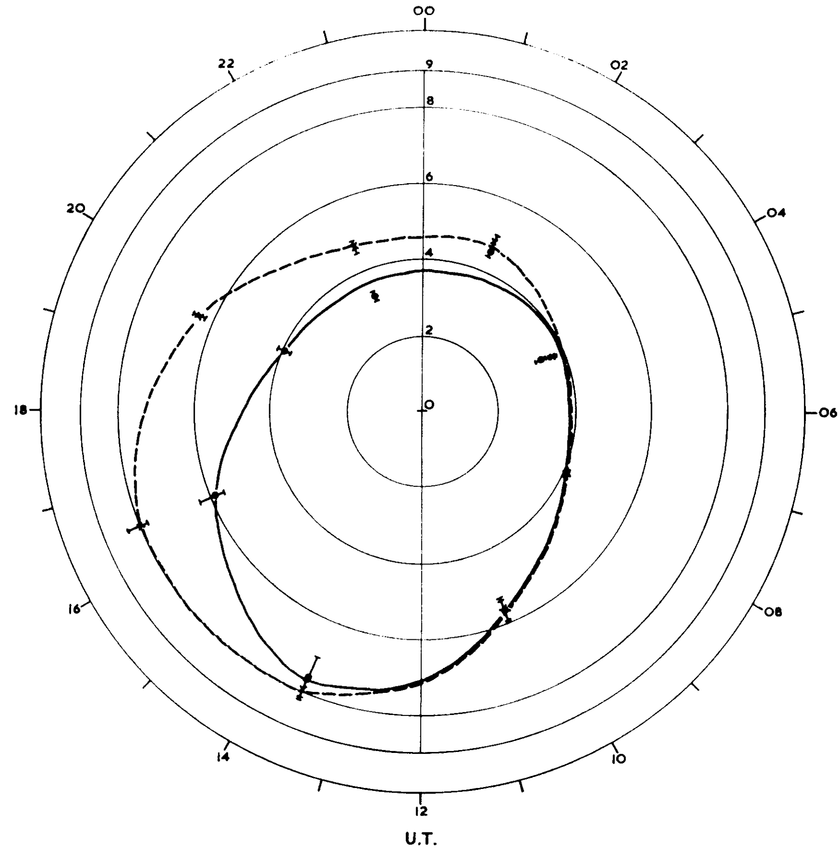


FIGURE 29

The level of K_p at which the probability of observing radio aurorae on the east limb of the echoing region reached 50 per cent during the I.G.Y.

●———● Diffuse radio aurorae.
× — — — × Discrete radio aurorae.

the diffuse radio aurorae observed from Halley Bay were extending to lower latitudes. In the morning hours very few diffuse radio aurorae were observed from Bluff when the magnetic disturbance was low as would be expected from the Halley Bay data, and in the interval 03–06 hr. when there is a suggestion of the development of a secondary peak in occurrence of diffuse radio aurora at Halley Bay for $K_p = 5$ such a peak appeared in the Bluff data at still higher levels of magnetic activity. Before local midnight the discrete radio aurora observed from Halley Bay was confined to high latitudes and was rare at Bluff even for high levels of magnetic disturbance. In the morning period the discrete oval extended to lower latitudes as the magnetic activity increased and was commonly observed at Bluff. No peak in activity would be expected within the latitude interval covered by the Bluff radar and none was found.

Observations from medium magnetic latitudes have invariably revealed the presence of two maxima in the diurnal variation of radio aurorae as described on p. 11. The peak in occurrence before local midnight has been found to contain mainly diffuse radio aurorae, whilst the radio aurorae associated with the peak in occurrence after local geomagnetic midnight are mainly discrete. These observations are in complete agreement with the results presented in Fig. 25.

Observations made at corrected geomagnetic latitudes of about 70° (e.g. Harang and Tröim, 1961; Leonard, 1962) have sometimes revealed a single maximum in the diurnal variation of radio aurorae. The observations at these high latitudes would be dominated by radio aurorae occurring in periods of weak magnetic disturbance when a single maximum would be expected from the results presented in Fig. 20.

A number of workers in the vicinity of the auroral zone have also reported three peaks in the diurnal variation of radio aurorae (e.g. Birfeld, 1960; Leadabrand, 1961; Egeland and Ericsson, 1962). One of these maxima tends to occur at local midnight (approximately), whilst the second occurs in the morning and the third in the early afternoon. Egeland and Ericsson (1962) noted, however, that the three peaks tended to occur at the higher levels of magnetic disturbance. In addition, the peak observed in the early afternoon was due mainly to the occurrence of diffuse radio aurorae. It may therefore be possible to associate the afternoon peak with the oval of diffuse radio aurorae which is most widely separated from the oval of discrete radio aurorae during high magnetic disturbances and on the evening side of the Earth. A morning peak in the occurrence of diffuse radio aurorae was found at College, Alaska, by Leadabrand (1961) and is clearly associated with the morning peak of diffuse radio aurorae observed at Halley Bay and Bluff, New Zealand, during moderate and intense magnetic disturbances, respectively. The peak just before midnight was found by Leadabrand (1961) to be due mainly to echoes from discrete radio aurorae which must have been located in the late evening sector of the oval of discrete radio aurorae. The probability of occurrence of discrete radio aurorae on the evening side of the Earth falls off rapidly towards noon as shown in Fig. 25, which may explain why Leadabrand did not observe a peak in the occurrence of these radio aurorae in the early afternoon.

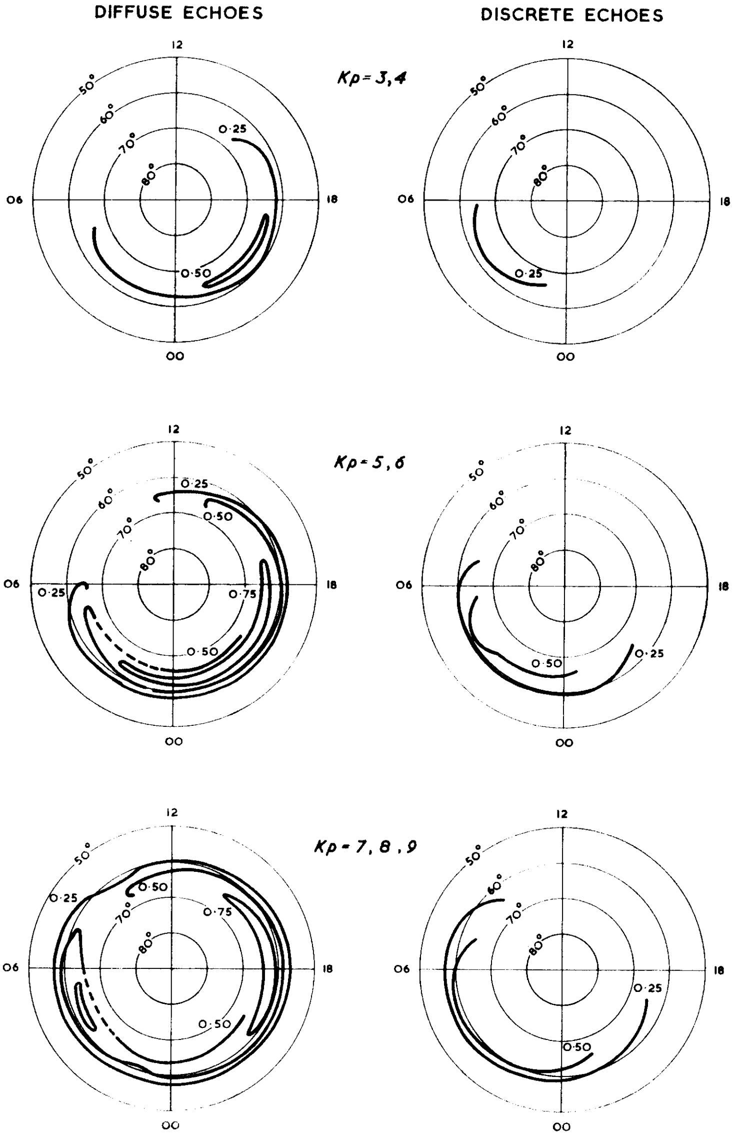


FIGURE 30

The probability of occurrence of diffuse and discrete radio aurorae within the range of latitudes surveyed by the radar at Bluff, New Zealand, during 1958. The coordinates are corrected geomagnetic latitude and time. (After Unwin, 1968.)

Unwin (1966*a*, *b*) has interpreted his distributions of discrete and diffuse radio aurorae in terms of spiral patterns as described on p. 24. The large equatorwards displacement of the oval of diffuse radio aurorae must have led Unwin (1966*b*) to associate these radio aurorae with the E spiral of geomagnetic activity. The evening discrete radio aurorae found at higher latitudes were assigned to the N spiral and the overlapping regions of the diffuse and discrete ovals in the morning were assigned to the M spiral. The interpretation of the distributions in terms of spiral patterns, however, necessarily emphasizes the regions of maximum activity, and the oval interpretation which is used here and which treats the whole distribution of each type of radio aurora is therefore thought to be preferable in a morphological study. In particular, these oval distributions bear a much closer relationship to the internal structure of the magnetosphere than do the spiral patterns.

4. *Possible relationships between the radio aurorae and the precipitation of energetic protons and electrons into the upper atmosphere*

The numerous examples of spiral patterns which have arisen in geophysical studies have been summarized by Nagata (1963) and his fig. 18 is reproduced here as Fig. 31. Nagata reached the following conclusions:

i. The geomagnetic M and A spirals approximately agree with the spiral patterns of hydrogen emission, auroral diffuse echoes, the r-type sporadic E ionization and night E ionization. As these two spirals are accompanied by maximum hydrogen emission, it seems very likely that they are caused mainly by proton precipitation. The M and A spirals seem to form approximately an oval pattern surrounding the geomagnetic pole, shifted down the 22–24 hr. meridian.

ii. The geomagnetic N spiral agrees roughly with the spiral patterns of visible aurora, auroral discrete echoes, and the f-type and a-type sporadic E ionization. As this spiral is characterized by visible aurora, it is doubtless caused by electron precipitation.

iii. The high-latitude spiral of ionospheric black-out is well correlated with auroral displays and seems to be an extension of the N spiral, the extended pattern forming an oval curve surrounding the geomagnetic pole but shifted towards the 03 hr. side as illustrated in Fig. 31.

When it has been added that the discrete radio aurorae are also found in the morning sector, where they extend equatorwards of the diffuse radio aurorae, the agreement between Nagata's conclusions and those reached here concerning the morphology of the radio aurorae is seen to be very close.

Nagata's suggestion that there is an association between discrete radio aurorae and electron precipitation

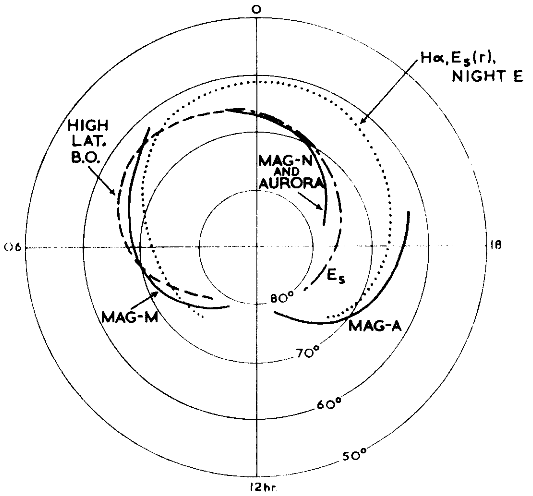


FIGURE 31

Spirals of the distribution of aurorae, magnetic agitation (magnetic M, N and A-spirals), ionospheric black-out (B.O.) auroral sporadic E (E_s) and hydrogen emission (H_α). (After Nagata, 1963.)

and between diffuse radio aurorae and proton precipitation is of considerable interest. A number of investigators have suggested that the discrete radio aurora may be associated with the more active visual forms (e.g. Currie and others, 1953; Bates and others, 1966), and on p. 50–52 it is shown that, of the two radio-auroral ovals, it is the oval of discrete radio aurorae which corresponds more closely with the visual auroral oval. A great deal of evidence has accumulated to the effect that auroral forms of naked eye visibility are produced by electron precipitation, which suggests that discrete radio aurorae are also associated with electron precipitation. Such an association has also been suggested by Unwin and Knox (1968, 1971) and by Sofko and Kavadas (1969).

If the associations suggested by Nagata do exist, the hydrogen aurorae should at least partially cross the visual auroral oval close to the midnight meridian. A large body of evidence suggesting that this is the case has now been accumulated both by ground-based observations (Montalbetti and McEwan, 1962; Stoffregen and Derblom, 1962; Derblom, 1968; Weins and Vallance Jones, 1969) and by satellite observations of precipitating particles (Johnson and others, 1967).

By far the most extensive study has been that by Wiens and Vallance Jones (1969). From observations made in the winters of 1963–65, using an approximately north–south chain of four patrol spectrographs in Canada, these authors reached the following conclusions:

i. Before midnight (about 21.00 hr.), particularly during periods of medium to strong geomagnetic activity, the maximum of the proton auroral oval is displaced about 3° equatorward of the maximum of the electron oval.
ii. After midnight (about 03.00 hr.) this displacement is probably reversed. At this time it is certain that there is a region of strong proton precipitation poleward of the electron oval. It is also certain that there is no region of proton precipitation of intensity comparable to that in the evening equatorward of the electron auroral oval.

The times given are geomagnetic times. At Halley Bay, geomagnetic times of 21.00 and 03.00 hr. correspond approximately to 23.00 and 05.00 U.T., respectively. The similarities between the conclusions drawn by Wiens and Vallance Jones and those reached here concerning the behaviour of the discrete and diffuse radio aurorae are very striking. In Table III a comparison is made between the latitudes of peak hydrogen emission as given by Wiens and Vallance Jones (converted to corrected geomagnetic latitudes) and the latitudes of peak occurrence of diffuse radio aurorae taken from Figs. 25 and 30. Again the agreement is very close and these observations therefore add a great deal of support to Nagata's suggestion.

TABLE III

COMPARISON OF LATITUDE DISTRIBUTIONS OF DIFFUSE RADIO AURORAE AND H_α EMISSION (CORRECTED GEOMAGNETIC COORDINATES)

Local magnetic time (hr.)	*Magnetic activity*	*Latitude of peak in H_α emission*	*Latitude of peak in occurrence of diffuse radio aurorae*
21.00	$2_o \leqslant K_p < 4_o$	65–68°	66°
21.00	$K_p \geqslant 4_o$	61–64°	62–64°
03.00	$2_o \leqslant K_p < 4_o$	67–69°	>66°
03.00	$K_p \geqslant 4_o$	66–68°	66°

At present very little direct evidence exists for an association between diffuse radio aurorae and proton precipitation. Galperin (1959), however, reported a close correlation between diffuse radio aurorae observed at 72 MHz and hydrogen emission from the aurora. Brooks (1967) has found it possible to explain pulsations in diffuse echoes following magnetic storm sudden commencements in terms of proton precipitation but not in terms of electron precipitation. It is also worth noting, in addition, that the extensive spread in range of diffuse radio aurorae is consistent with such an association.

Bates and others (1969) found an association of radio aurorae with electron precipitation simultaneously observed by satellite. No similar association with proton precipitation was found. However, these authors pointed out that their radar apparently did not detect diffuse radio aurorae, probably because of the low system sensitivity of the College HF radar compared with the VHF and UHF radars which do detect such echoes. The corrected geomagnetic latitude of College, in fact, is 64·9° and it is therefore clear from Figs. 25 and 30 that throughout the evening period when the regions of proton and electron precipitation are most widely separated, and when any association between diffuse radio aurorae and proton precipitation should be sought, the diffuse radio aurorae would have been either overhead or to the south at College and therefore not observable.

In the absence of simultaneous observations of diffuse radio aurorae and of proton precipitation, either observed by ground-based photometers or by satellites, the existence of an association between these phenomena cannot be established with certainty though there is now much evidence for this association. If future observations do verify the conclusions reached here, then radio-auroral observations will be able to give important information on the precipitation of energetic protons and electrons into large regions of the polar upper atmosphere. Such information should provide tests of auroral theories when these have been sufficiently developed. At present, very few theories have mapped out the main regions of proton and electron precipitation. Kavanagh and others (1968) have calculated the drift paths of 1 keV protons through the magnetosphere under the influence of solar wind-induced convection and have found that these drift closer to the Earth on the evening side and gain kinetic energy. Wiens and Vallance Jones (1969) have suggested that this process may be responsible for the 21.00 hr. equatorwards bulge and evening asymmetry in the proton precipitation. Speiser (1969) has suggested a neutral line accelerating mechanism which is capable of producing a precipitation pattern of protons and electrons very similar to that found by Wiens and Vallance Jones. The adiabatic drift theory of Taylor and Hones (1965), however, predicts that proton precipitation should occur equatorwards of the electron precipitation at all times and is therefore not in accord with the observations.

5. *Possible origins of the diffuse radio aurorae*

Farley (1963*a*, *b*) and Buneman (1963) pointed out the similarity of the ionospheric current system to the "two-stream" instability system of plasma theory and suggested that the instabilities may generate longitudinal acoustic plasma waves which may then give rise to the radio aurora. The waves grow whenever the average drift velocity or streaming velocity of the electrons relative to the ions in the E region of the ionosphere exceeds a certain critical value which is slightly greater than the plasma acoustic velocity for the medium. The most easily generated waves are those propagating in the direction of current flow and perpendicular to the magnetic field, so that the irregularities will be aspect sensitive, and the velocity of these waves is just slightly higher than the plasma acoustic velocity in the medium.

It has been suggested by Unwin and Knox (1968) that the diffuse radio aurorae are produced by the two-stream instability, and Gadsden (1967) has shown that the production of the ion-acoustic waves in the E region requires only the presence of a sufficiently intense electric field and is only weakly dependent on the ionization density. Unwin (1968) has suggested that the electric fields giving rise to the evening and morning diffuse radio aurorae have rather different origins. He considered that the electric field which drives the westwards auroral electrojet also produces the early morning peak in diffuse echo occurrence but that the evening diffuse radio aurorae are caused by the electric field which is produced in the ionosphere by the convection of magnetospheric material driven by the solar wind.

A highly simplified model of the magnetospheric convection was used by Unwin (1968) to deduce the regions of the ionosphere in which the two-stream instability might occur. This model was symmetrical about the 06.00–18.00 hr. meridian and consequently predicted peaks in the occurrence of diffuse radio aurorae at these times. To bring his theoretical predictions into line with the observed peak in occurrence at about 21.00 hr., however, Unwin resorted to a pattern of magnetospheric convection due to Nishida (1966) which would be observed from a point fixed with respect to the Sun–Earth line and which therefore included effects due to the Earth's rotation. Such a pattern of convection and its projection into the ionosphere along magnetic field lines would not be seen by an observer rotating with the Earth, so that Unwin's explanation of the discrepancy between his theory and the observations is not valid.

Electric fields in the same sense as those associated with the magnetospheric convection will be produced as a result of the separation of energetic protons and electrons onto different magnetic field lines in the magnetosphere. These electric fields should also be most intense where the separation of the regions of proton and electron precipitation is greatest, whilst those resulting from convection induced in the magnetosphere by the solar wind would be quite extensive in longitude. If it is supposed that, usually at least, it is the combination of these two systems of electric fields which results in electric fields greater than the critical value required for the production of the two-stream instability, it may be possible to reconcile the suggestion of Unwin and Knox (1968) and Unwin (1968) as to the nature of the diffuse radio aurorae with the observations previously discussed. In particular, such a model of the electric fields would result in the most frequent occurrence of diffuse radio aurorae at around 21.00 hr., when the separation of the belts of proton and electron precipitation is greatest, and in the appearance of diffuse radio aurorae equatorwards of discrete radio aurorae in the evening and polewards of these in the morning hours.

Whilst the production of ion-acoustic waves in the E region of the ionosphere requires only the presence of an electric field and is independent of the ionization density (Gadsden, 1967), their observation by a given radar requires an ionization density great enough to give echoes which are sufficiently intense to be detected. The enhancement of electron density produced by the precipitation of protons into the ionosphere may therefore play some part in the production of diffuse radio aurorae by the mechanism proposed by Unwin and Knox (1968).

The most direct evidence that ion-acoustic waves do occur in the radio aurora was obtained by Hofstee and Forsyth (1969) at a time when the radio aurora was predominantly diffuse (see McDiarmid, 1970). These authors noted, however, that ion-acoustic waves may not be the predominant source of radio-wave scattering. Difficulties in the interpretation of the radio-auroral observations on this model have also been found by Ecklund and Gadsden (1967), and on p. 36–37 it is shown that it is not possible to account for the velocities of the diffuse radio aurorae deduced from range shifts in terms of the propagation of ion-acoustic waves. Therefore, whilst the two-stream instability does occur in the auroral ionosphere, this does not appear to be the only mechanism involved in the production of even one type of radio aurora.

VII. MOVEMENTS OF THE ECHOING CENTRES

1. *Interpretation of the film records*

Since the region over which the echoing ionization could be observed from Halley Bay was limited by the specular condition of reflection, the observed radio-auroral motions were essentially the components of the real motions along the echoing region. Because of this observational limitation and through the use of fixed aerials, it was not possible to determine the true directions of motion of the echoing centres. Observations of the radio aurora from Invercargill, New Zealand (Unwin, 1959), and from Tromsö, Norway (Harang and Tröim, 1961), have revealed, however, that the directions of motion are predominantly east–west. Observations of the motions of visual aurorae have generally been resolved into north–south and east–west components and most investigators have found that the east–west motions are generally faster than the north–south motions by at least a factor of 3 (Cole, 1963). On the basis of this evidence, it is assumed throughout the analysis which follows that the true directions of movement of the radio aurorae were east–west.

The radial velocities of radio aurorae were determined from their movements in range as revealed on the continuously moving film records. Since the echoing regions could be continuously observed for up to 4 min., accurate determinations of their velocities were possible. The measurements were made with the aid of a pencil follower as previously described. The velocities so determined were recorded to an accuracy of $\pm$ 5 m. sec.$^{-1}$, an accuracy greater than could usually be justified since the echoes were rarely sharply defined. Because of the high precision of the pencil follower, very few radio aurorae with zero velocity were recorded.

Whilst the radial velocities of the discrete radio aurorae were readily determined from the range–time records, it was frequently impossible to determine the velocities of the diffuse radio aurorae. The extension in range of the diffuse echoes was frequently determined by the intersection of the aerial beam with the echoing ionization. Under those circumstances, this echo type, which has no structure visible on the film records, showed no movement in range. In consequence, the velocities of the diffuse echoing centres were frequently underestimated and the mean hourly velocities discussed here are not the true mean velocities for this type. In determining the radial velocities of the structured diffuse radio aurorae it was the velocity of the discrete structure that was measured.

2. *Dependence of the motions on magnetic disturbance*

The set of graphs in Fig. 32 shows, for echoing centres on the east limb in the 3 hr. period 21.00–00.00 hr. U.T., the median values and quartile ranges of the mean hourly radial speeds when grouped according

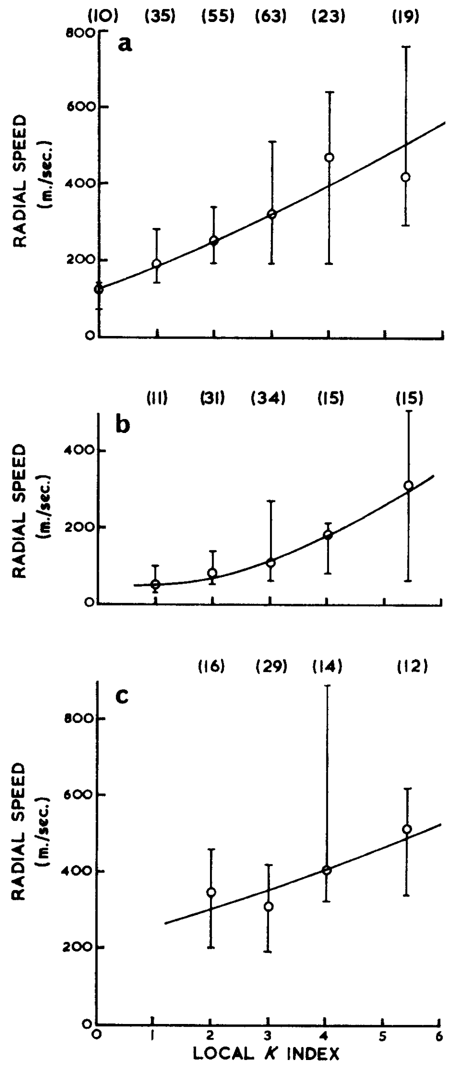


FIGURE 32

The median values and inter-quartile ranges of the mean hourly radial speeds of (a) discrete, (b) diffuse and (c) structured diffuse radio aurorae at different levels of local magnetic disturbance. East limb observations cover the period 21–00 U.T.

to the value of the Halley Bay *K* index. The results for local *K* values of 5 and 6 have been combined and the bracketed figures are the numbers of hourly mean values used. The mean hourly speeds were derived from the magnitudes of the measured mean velocities which, for the time interval used, were predominantly westerly. The three echo types are treated separately. For each echo type a wide range of radial velocities was recorded at each level of magnetic disturbance. Despite the scatter in the results, all three graphs show an increase in the average speed of the echoing centres with increase in the level of magnetic disturbance.

Graphs (a) and (c), for discrete and structured diffuse radio aurorae respectively, are closely similar. Since the measured velocities of the structured diffuse radio aurorae were the velocities of the structure, this result gives support to the assumption made throughout this report that the structured diffuse radio aurorae are produced by the simultaneous occurrence of diffuse and discrete radio aurorae at the same range. Graph (b) for diffuse radio aurorae shows similar trends to graphs (a) and (c) but the speeds recorded were on average much lower than those for the discrete and structured diffuse radio aurorae. This result is to be expected in view of the limitations imposed on velocity measurements for the diffuse radio aurorae which were discussed on p. 35.

The results of Fig. 32a for discrete echoes are similar to those found by Unwin (1967) for this echo type. Unwin noted that the velocities of the discrete radio aurorae observed from Bluff, New Zealand, increased with the local magnetic K index, as found here, and also with increasing magnetic latitude. The corrected geomagnetic latitudes covered by the east limb of the echoing region observable from Halley Bay lie just polewards of the highest corrected geomagnetic latitudes observable by Unwin and the measured velocities of the discrete radio aurorae observed on the east limb were in fact slightly higher, at each level of magnetic disturbance, than those found by Unwin. This increase in velocity with latitude was also noted by Bowles (1954).

The results of Fig. 32b for diffuse echoes are not, however, in agreement with those of Unwin (1967), who found that the velocities of the diffuse and diffuse-with-structure echoes observed in the afternoon and evening hours from Bluff had a negligible dependence on the local magnetic K index. The radial velocities of diffuse radio aurorae observed from Halley Bay showed a strong dependence on magnetic disturbance and were also frequently greatly in excess of the velocity of 310 m. sec.$^{-1}$, which was found by Unwin and which he has suggested is the velocity of ion-acoustic waves. Bullough and Kaiser (1955) also reported a large proportion of diffuse radio aurorae with radial velocities much greater than those found by Unwin (1967); in fact, 37 per cent had radial velocities over 500 m. sec.$^{-1}$. The plasma acoustic velocity is given by

$$\left(\frac{2kT}{m_i}\right)^{\frac{1}{2}},$$

where k is Boltzman's constant, m_i is the average ionic mass, and T is the absolute temperature of the medium. Unwin considered that the velocity of 310 m. sec.$^{-1}$ implied a gas kinetic temperature of about 240 K. Velocities of over 500 m. sec.$^{-1}$ in a medium of the same composition would therefore imply temperatures over 600 K and the highest radial velocities recorded by Leadabrand and others (1965), namely 750 m. sec.$^{-1}$, would imply temperatures of about 1,400 K. These higher temperatures are much greater than those normally measured in aurorae (Omholt, 1967), and on p. 46–50 it is demonstrated that diffuse radio aurorae do not always occur at the same positions as visual aurorae. It thus seems to be highly unlikely that the velocities measured by Unwin (1967) for diffuse radio aurorae were actually those of ion-acoustic waves.

3. *Directions of motion of the echoing centres*

Fig. 33 shows, as a function of Universal Time, the numbers of westwards and eastwards radial velocities observed on the east limb of the echoing region for all types of radio aurora. The overall shapes of the curves

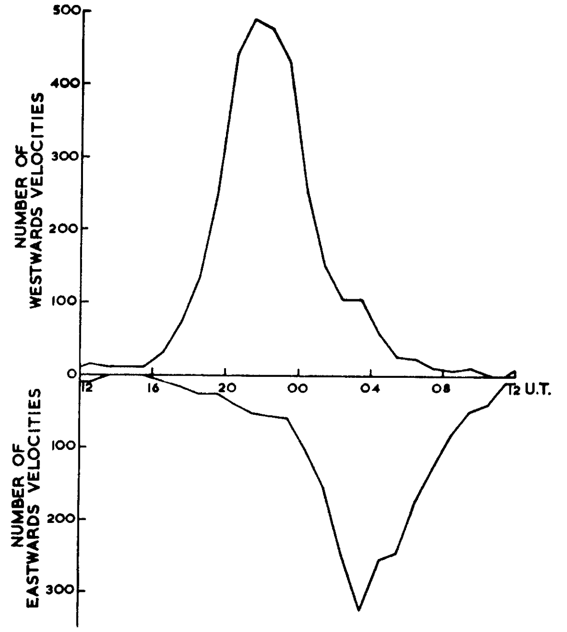


FIGURE 33

Diurnal variations in the number of radio aurorae with eastward and westward velocities.

are determined largely by the diurnal variation in occurrence of the echoing irregularities. The graphs show a smooth change-over from westerly velocities in the evening to easterly velocities in the morning. At times near local midnight the situation is complex. The results of Fig. 33 closely resemble those found at Jodrell Bank (Bullough and Kaiser, 1955), Invercargill (Unwin, 1959) and Kjeller (Harang and Tröim, 1961). Observations from sites at higher corrected geomagnetic latitudes, such as College (Nichols, 1959) and Tromsö (Harang and Tröim, 1961), have revealed far less regular patterns of movement, however, and many of the observations were interpreted in terms of equatorwards motions. Cole (1963) has suggested that these differences may be explained in terms of the relation of the different regions viewed from the

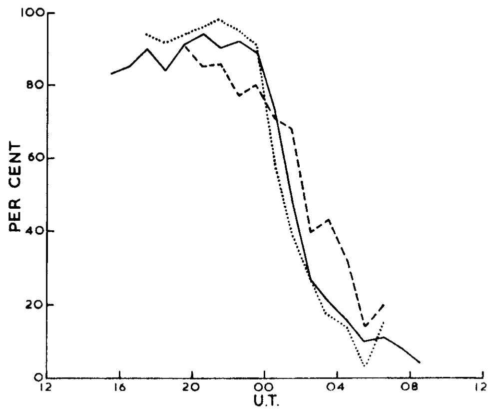


FIGURE 34

Diurnal variations in the proportion of radio aurorae with westerly velocities.

– – – – – Diffuse radio aurorae.

———— Discrete radio aurorae.

……………… Structured diffuse radio aurorae.

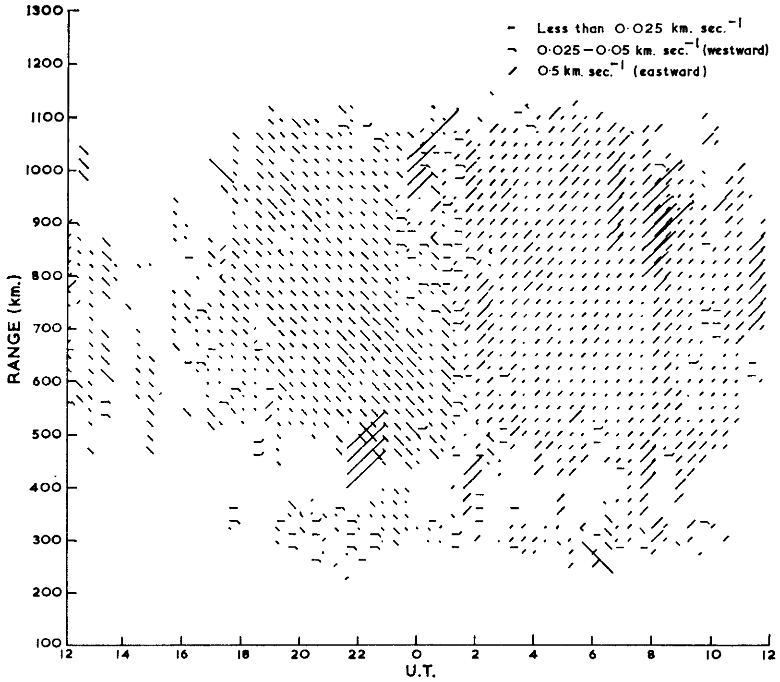


FIGURE 35

The mean radial velocities of discrete radio aurorae observed on the east limb. Range interval 25 km., time interval 24 min.

various observing stations to the pattern of polar ionospheric currents, with which the motions are thought to be associated.

For the three different echo types, the percentages of echoing centres showing westerly velocities are presented in Fig. 34 as a function of Universal Time. All three graphs show the same general trend but the times of reversal of velocities, defined here as the time at which the radio aurorae were equally divided between the two directions of motion, are different. The observed differences between the time of reversal of velocities for the structured diffuse radio aurorae and the corresponding times for the other two types are not statistically significant by the χ^2 test. The difference of about 1 hr. observed for the diffuse radio aurorae, however, is statistically significant at the 1 per cent level.

Harrison (1962), from his observations at Halley Bay during the I.G.Y., drew the interesting conclusion that the time of reversal of velocities probably varies with geomagnetic latitude, with an earlier reversal at the higher geomagnetic latitudes. Mass plots of the velocity data for the different types of radio aurora were prepared from the I.Q.S.Y. data and, as an example, that for discrete radio aurorae observed on the east limb is presented in Fig. 35, where the mean velocity is plotted for each 24 min. interval in Universal Time throughout the day and for each 25 km. interval throughout the observable range. From this diagram and a similar diagram for the west-limb observations, the times of reversal of velocities were determined for each 100 km. interval in range. These results are plotted in Fig. 36, which shows the geomagnetic time of velocity reversal as a function of geomagnetic latitude (centred dipole coordinates), together with an estimate of the probable error. No account has been taken of the variation of geomagnetic time with solar declination, which was assumed to be zero. The results in Fig. 36 confirm Harrison's conclusion which was based upon more limited data.

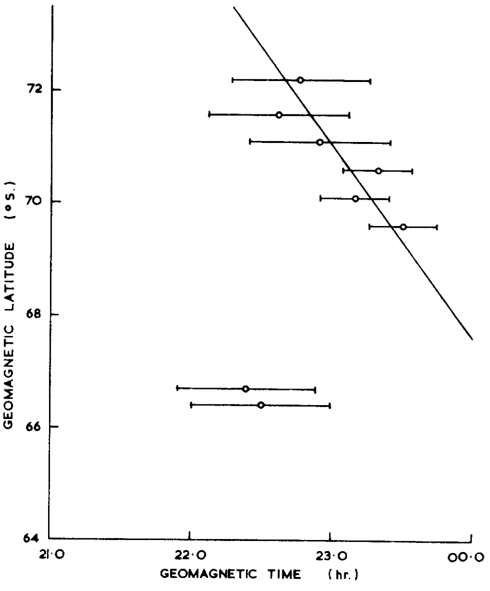


FIGURE 36

The variation of the geomagnetic time of velocity reversal with geomagnetic latitude (centred dipole coordinates).

It must be pointed out that the times of reversal discussed here were determined by the times at which the mean velocities of the irregularities were zero. These times are in part dependent on the relative magnitudes of the easterly and westerly velocities. The times thus determined are not necessarily the same, therefore, as those times at which the radio aurorae were equally distributed about the two directions of motion. Examination of the mass plot of mean velocities in Fig. 35 suggests, however, that any discrepancies arising due to the use of the different definitions should be very small for these observations.

The general trend in the time of velocity reversal with latitude changed for the lower-latitude, west-limb observations. It is suggested here that this change resulted from the different diurnal variations of discrete radio aurorae on the two limbs of the echoing region. Very few discrete radio aurorae were observed on the west limb of the echoing region during the evening. Consequently, one would expect the minimum in the average velocity of the irregularities to be displaced towards the evening hours as observed. Since the morning and evening peaks in the occurrence of discrete radio aurorae on the east limb were similar, the times of reversal for this limb are thought to be far more reliable than those for the west limb.

The times of reversal of the diffuse and structured diffuse radio aurorae on the east limb were found to be the same as those of discrete radio aurorae on that limb, within the error of these determinations. Unfortunately, the observations of these radio aurorae on the west limb were too limited for their times of velocity reversal on that limb to be determined with any certainty. There was no evidence in this analysis for different times of reversals of the different types of radio aurorae, and it is suggested that the later time of reversal of the diffuse radio aurorae found from Fig. 34 resulted from the fact, noted on p. 27, that these were to be found, on average, at lower geomagnetic latitudes than radio aurorae of the other two types.

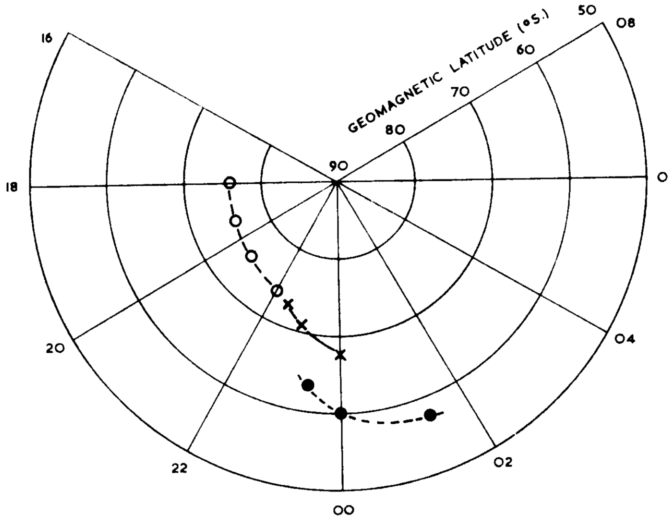


FIGURE 37

The variation with geomagnetic latitude of the geomagnetic time at which radio-auroral motions reverse direction using observations from Dumont D'Urville (o----o; Bullough, 1961), Bluff (●----●; Unwin, 1967) and Halley Bay (×——×).

A very similar trend in the time of velocity reversal with geomagnetic latitude was found by Unwin (1967) using observations made from Bluff, New Zealand, during the I.G.Y. The results from the I.Q.S.Y. east-limb observations and those found by Unwin have been combined here in Fig. 37. The agreement between these two sets of data would have been greatly improved had corrected geomagnetic coordinates been used rather than centred dipole coordinates. To convert Fig. 37 to corrected geomagnetic latitudes, the Halley Bay and Bluff results should be moved about 4° equatorwards and 3° polewards, respectively. Centred dipole coordinates have been used here, however, in order that the observations of Bullough (1961) might be included, since it was impossible to convert these to corrected geomagnetic coordinates without recourse to the original data.

During the I.G.Y., Bullough (1961, 1962*a*, *b*) made observations of radio aurorae from Dumont D'Urville, Antarctica, which is at 75·8° S. geomagnetic latitude, well inside the auroral zone. Bullough measured two kinds of velocities: those of short-lived reflecting regions and those of long-lived reflecting groups, each of which comprised numerous reflecting regions, and suggested that it is the latter motions which give the better overall impression of the mean trends. Fig. 11c from Bullough (1961) is reproduced here as Fig. 38. The coordinates are geomagnetic colatitude and geomagnetic hour angle (G.H.A.). Bullough (1961) considered that diagrams such as this provide evidence for the existence of inner and outer zones of activity, the outer being associated with the conventional auroral zone. In the early evening (G.H.A. 240–280°), radio aurorae were observed in both the inner and outer zones. The division into two zones was not marked and southerly motions predominated. In the evening (G.H.A. 280–350°), there was a clear division of the activity into two zones with mainly westerly motions in the outer zone, and easterly motions in the inner zone. The simultaneous occurrence of activity in the inner and outer zones was very rare. During the night (G.H.A. 340–40°), the two zones merged into a single zone and the motions were westerly. Throughout the remainder of the day (G.H.A. 40–240°), there was very little outer-zone activity and the motions were indeterminate, possibly due to insufficient data.

The dashed line in Fig. 38, separating the regions in which eastwards and westwards velocities were observed in the evening period, has been added to Bullough's original diagram. This line has also been included in Fig. 37 where it may be seen that the variation in the time of the velocity reversal with geomagnetic latitude continues, apparently unchanged in form, into the polar cap. The results presented in Fig. 38, it should be noted, refer to the summer months and there was no evidence of an inner zone of radio aurorae during the winter. Bullough (1962*b*) has suggested that the formation of the localized blobs of ionization responsible for the radio-auroral echoes might be somewhat inhibited in the absence of sunlight. However, if Bullough's observations were averaged over the winter, spring and summer seasons, as was the case with the Halley Bay observations, the inner zone would still appear though with less prominence.

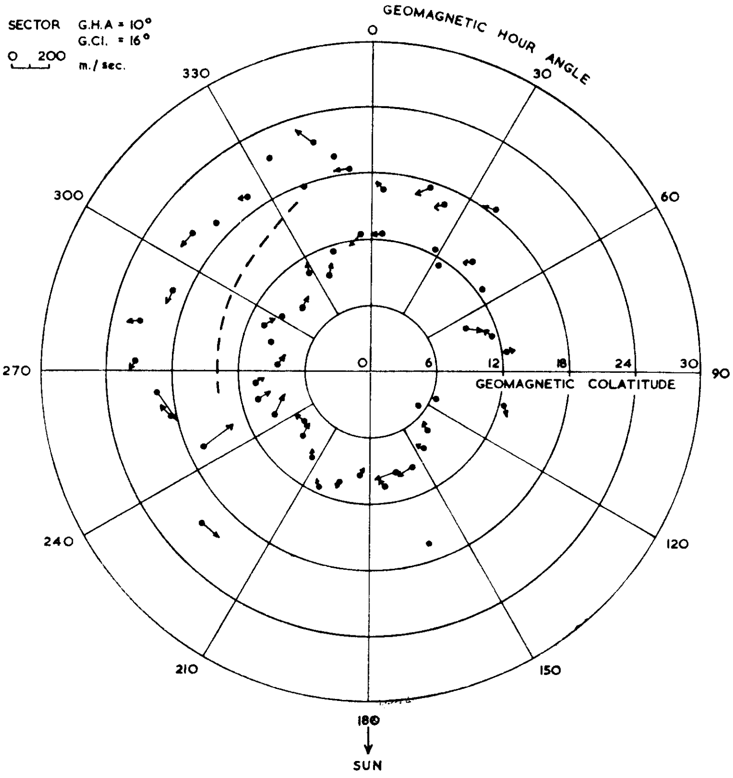


FIGURE 38

The weighted mean displacements of radio-auroral groups: November and December 1957, January 1958 (after Bullough, 1961). The dashed line, indicating the region within which the motions of radio aurorae reverse direction, has been added to the original diagram.

The radio aurorae observed by Bullough in the outer zone during the evening appear to be associated with those observed from Halley Bay at the same time of day but were evidently not the same irregularities, since they were only weakly aspect sensitive and had relatively low average velocities. The easterly motions observed by Bullough in the inner zone during the evening appear to be an extension into the polar cap of the easterly motions observed in the morning from Halley Bay. Very few outer-zone radio aurorae were observed from Dumont D'Urville which might have been associated with those observed in the morning from Halley Bay, however, and those inner-zone radio aurorae observed lay at too high a geomagnetic latitude to have been observable from Halley Bay.

4. *Discussion*

The motions observed in the radio aurora cannot possibly be real mass motions. As was shown earlier, the velocities observed greatly exceed, at times, the velocity of sound in the E region. In addition, these velocities are frequently an order of magnitude higher than those observed for ordinary E-region ionization and meteor trails. The latter behave quite normally when in the vicinity of radio aurorae (Booker and others, 1955; Bullough and Kaiser, 1955).

Cole (1963) has suggested that the motions of radio aurorae correspond to the motions of the sources of the ionization in the magnetosphere. However, Bullough (1961) noted the similar behaviour of visual aurorae and outer-zone radio aurorae observed in the winter months, and the similarity of the distributions in latitude of the radio and visual aurorae observed from Halley Bay is demonstrated on p. 50–52. Therefore, since the eastward motions of the radio aurorae observed from Halley Bay appear to be continuous across the boundary of closed field lines in the magnetosphere, which lies on the poleward edge of the visual auroral oval, Cole's interpretation of the motions now seems unlikely to be correct.

The observations are not, however, inconsistent with the suggestion of Bullough and others (1957) that the echoing irregularities move in the direction of the electron current in the auroral electrojets. The variation with latitude of the time of reversal of the radio-auroral velocities is very similar to that found by Harang (1946) in the time of the reversal in sign of the disturbance of the horizontal component of the Earth's magnetic field. Harang's results are reproduced here as Fig. 39, which shows contours of equal disturbance. In obtaining this result, Harang did not mix widely different levels of magnetic disturbance and used a chain of closely spaced stations along a geomagnetic meridian. In addition, although the agreement is by no means exact, the pattern of radio-auroral motions which emerges from the above discussions bears many of the features of the average equivalent ionospheric current system, DP, proposed

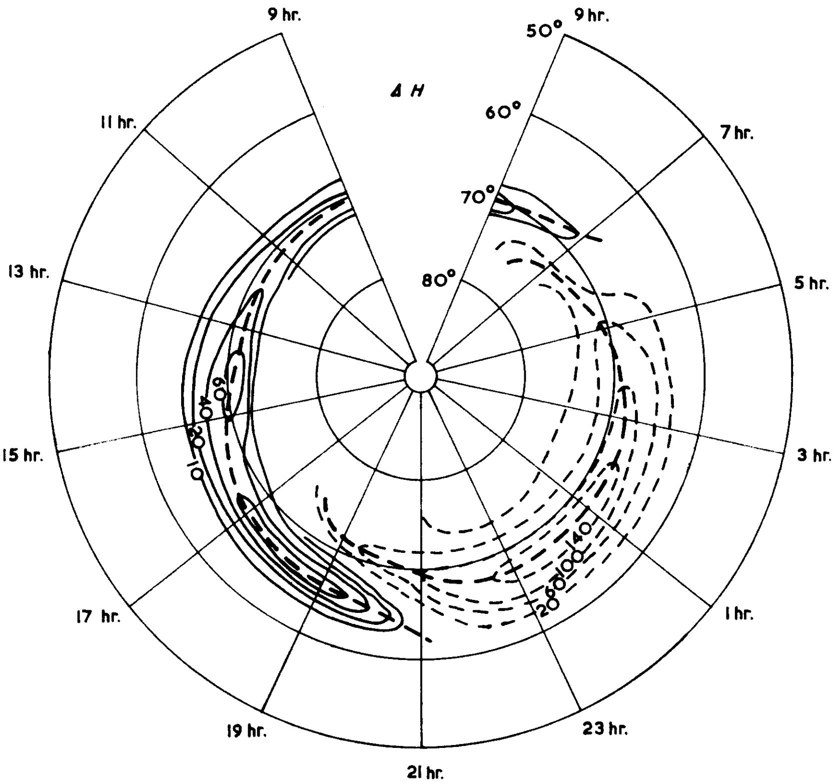


FIGURE 39

Contours of equal disturbance of H, the horizontal component of the Earth's magnetic field.

———— Positive disturbances.

— — — — Negative disturbances.

The local standard time used is approximately 1–1·5 hr. earlier than the corresponding geomagnetic time. (After Harang, 1946.)

by Feldstein and Zaitzev (1965) and shown in Fig. 40. This equivalent current system has two vortices with a westward electrojet within the bounds of the auroral oval and a separate eastward electrojet in the evening hours. This pattern was derived from winter observations in the Northern Hemisphere during the I.G.Y. The motions of the radio aurora are in the same direction as the flow of electrons in this current system. The large velocities of radio aurorae are also consistent with the theoretical predictions of Kaiser and others (1969) that for strongly field-aligned irregularities, such as those observed from Halley Bay, these are the drift velocities of electrons in the ionospheric current systems.

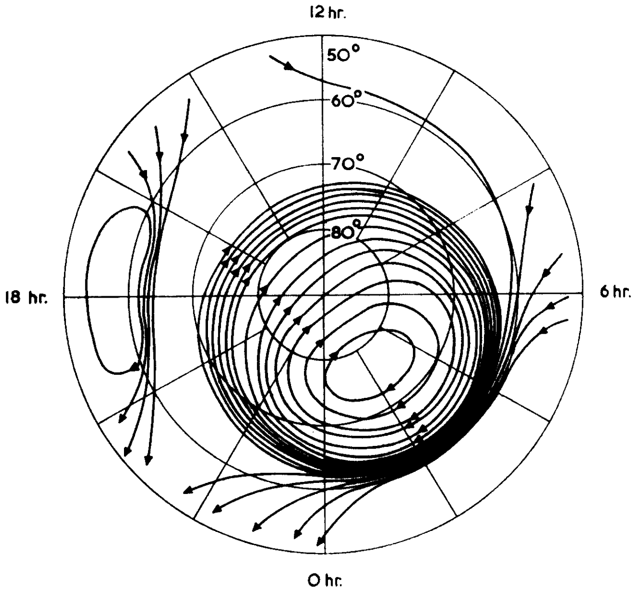


FIGURE 40

The equivalent ionospheric current system, DP, according to Feldstein and Zaitzev (1965).

VIII. ASSOCIATIONS BETWEEN RADIO AND VISUAL AURORAE

DETAILED visual observations of the aurora are necessarily restricted to those periods in which the sky is not obscured by cloud, fog or drifting snow. Observations are further limited to the hours of darkness, which are non-existent in the polar summer, and even the value of observations made on clear nights may be reduced if the moon is above the observer's horizon.

The discovery of the radio aurora and of its association with discrete visual aurorae (e.g. Lovell and others, 1947) led to the suggestion by many authors that this phenomenon should provide a means of observing the aurora continuously, since radio waves in the frequency range used are unaffected by the factors listed above. However, though the existence of an association between the radio and visual aurorae was quickly noted, there is still much controversy concerning the nature of this association.

1. *Temporal and spatial associations between the two phenomena*

The tendency of radio and visual aurorae to occur in the same hour, whatever their relative positions in the sky, is examined in Table IV. Here, attention has been confined to those hours in which the radar was operating satisfactorily, and in which the sky was clear and dark. "Clear" implies that no cloud was present south of Halley Bay and "dark" implies that the Sun was more than 12° below the horizon and the moon less than half full. The analysis included all such data from 11 April 1965, when the radar began to operate on all three aerials, through to 30 September 1965, when the conditions for darkness ceased to hold. Application of the χ^2 test to the distribution of Table IV shows that the temporal association between the

TABLE IV

COMPARISON OF VISUAL AND RADIO AURORAL OCCURRENCES

	Visual aurora present	*Visual aurora absent*	*Total*
Radio aurora present	50	0	50
Radio aurora absent	156	69	225
Total	206	69	275

radio and visual aurorae is highly significant, radio aurorae being observed from Halley Bay only when visual aurorae were also observed.

It is a fairly simple matter, however, to show that the radio echoes could not have been produced in all cases by direct reflections from aurorae observed visually. In Fig. 41 the maximum elevation reached by the radio aurora in a particular hour is plotted against the maximum elevation reached by the visual aurora in the same hour, for hours in which the sky was clear and dark and in which radio aurorae were observed. Logarithmic scales have been used in plotting the graph. Attention has been confined to those hours in which the visual form with maximum elevation was either an arc or a band, whether homogeneous or rayed. Measurements of the maximum elevations of the visual aurorae observed from Halley Bay were made by Sievwright (1967*a*, *b*) at quarter-hourly intervals on a routine basis and more frequently when the aurora was very active. For each hour the lowest of the range intervals listed in Table V in which radio aurora occurred was noted and a lower limit was set to the elevation of the radio aurora by determining the elevation angle corresponding to the greatest range within each range interval. These elevation angles are listed in Table V and were determined for an assumed height of the reflecting region above the Earth's surface of 110 km. This approach, though rather crude, is sufficiently accurate for present purposes.

Only one point lies exactly on the dotted line drawn in Fig. 41, which is the requirement for the elevation angles of the two phenomena to be equal. This is not surprising since the azimuths in which the elevations of the two phenomena were determined were usually very different. The echoing region observable from Halley Bay lies approximately along a parallel of geographical latitude, whilst the auroral forms are aligned approximately along parallels of geomagnetic latitude. Examination of Fig. 6 (p. 10) therefore shows that

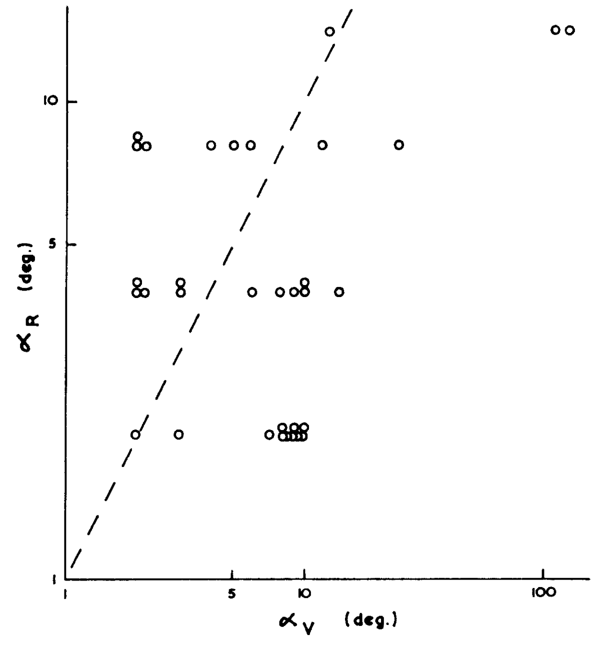


FIGURE 41
Comparison of the maximum elevations reached by the radio aurorae, α_{R}, and visual aurorae, α_{V} (logarithmic scales).

TABLE V

LOWER LIMITS TO THE ELEVATIONS OF RADIO AURORAE OCCURRING IN SELECTED RANGE INTERVALS

Range interval containing radio aurora (km.)	*Lower limit to elevation of radio aurora* (deg.)
300–400	14
500–600	8
700–800	4
900–1,000	2

the elevation angles of the points at which visual aurorae intersect the echoing region will always be less than or equal to the maximum elevation angles of the visual forms. It is thus possible to explain satisfactorily the appearance of points below the dotted line in Fig. 41. However, no less than 35 per cent of the points lie above this line.

The only way in which the elevation angles of the radio aurorae may have been overestimated, thus giving rise to points above the dotted line in Fig. 41, was by the assumption of too great a height of reflection, and it has not been possible to determine the reflection heights from the radio data because the beam widths of the aerials used were too great. However, if it is assumed that the anomalous radio echoes in Fig. 41 were produced by specular reflection from the visual aurorae, the range of the reflection point will vary only very slowly with elevation angle. The range of the base of the visual form may therefore be assumed equal to the range of the corresponding radio aurora and the height of the base of the visual form may thus be calculated using this range and the visually determined elevation angle. The frequency distribution of these calculated heights, for all of the anomalous results of Fig. 41, is shown in Fig. 42. The mean value of the heights is 76 km. and their range extended from 103 km. down to 49 km. Many of the heights thus determined were therefore much lower than those known for the lower borders of visual forms (e.g. see Egeland and Omholt, 1967). Moreover, the heights determined here are the maximum possible heights of the bases, since it has been assumed that the elevation angles of the points at which the visual forms intersected the echoing region were equal to the maximum elevations of these forms. The anomalous results of Fig. 41 cannot, therefore, be explained on the hypothesis that the so-called auroral radio echoes are produced only by reflection of radio waves from aurorae which are observed visually. On at least 35 per cent of the occasions considered here the radio aurora extended equatorwards of the visual aurora.

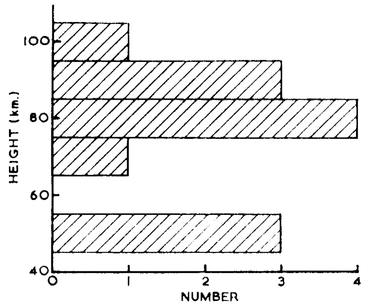


FIGURE 42

The heights of the bases of visual aurorae deduced from radar ranges and visually determined elevations.

2. *Association of radio aurorae with different visual forms*

Comparison of the diurnal variation curves for the different types of radio aurorae (Fig. 12) with those given by Sievwright (1967*b*) for different visual forms reveals no clear evidence of any associations.

Relationships have been sought between the brightnesses of different visual forms and the amplitudes of echoes from different types of radio aurorae. When the brightest visual form also had the greatest elevation, it was assumed that that form was associated with the echo of maximum amplitude obtained in that hour, otherwise the data were not included in the analysis. In addition, only those hours were included in which some radio aurora accompanied the visual aurora.

In Table VI the brightnesses of homogeneous arcs, homogeneous bands, and rayed arcs and bands treated as a single class are compared with the amplitudes of echoes from accompanying discrete and diffuse radio aurorae. The expected numbers of occurrences of echoes of each amplitude index when visual aurorae of each brightness class were present, derived on the assumption that there was an even distribution amongst the classes, are shown in brackets. Clearly, there is no evidence that the amplitudes of the echoes were related to the brightnesses of any of the visual forms considered.

The observations are in complete agreement with those of Harrison (1962) and, in essence, with those of Gadsden (1959*b*), both of whom used antenna beam widths similar to those used in the present study. There is a pronounced disagreement, however, between these results and those of Kelly (1965), who used an antenna of much smaller beam width. Variable beam-filling must have played a very large part in determining the amplitudes of echoes obtained from Halley Bay and may have masked a real relationship between the echo amplitudes and the brightnesses of the visual aurorae.

Other evidence is presented on p. 50 which suggests that both diffuse and discrete radio aurorae are closely associated with homogeneous arcs. It has not been possible to determine to what extent the radio aurorae are associated with other visual forms.

3. *Latitude separation of the radio and visual aurorae*

In view of the results presented on p. 43–45 concerning their spatial relationship, it is natural to enquire to what extent the radio aurorae extend equatorwards of the visual aurorae. The analysis is complicated by the fact that most observations of the radio aurora were made in regions far removed from the geomagnetic meridian through Halley Bay, whilst most measurements on visual aurorae were made close to where they crossed that meridian. The analysis has been confined to those periods when homogeneous arcs were present, since it was only for these forms that both the maximum elevations and the azimuths of the points of maximum elevation were determined by the visual auroral observer at his routine quarter-hourly observations. In all cases these azimuths were very close to that of geomagnetic south and it has therefore been possible to determine the geomagnetic latitudes of the arcs from their maximum elevations alone without introducing significant errors. A mean value of 100 km. has been assumed for the heights of the lower borders of homogeneous arcs. These vary very little with position along the arcs so that the azimuths of the points of maximum elevation give the directions of the normals to the arcs at those points. It is therefore possible to determine the range at which a particular arc should intersect the echoing region using only the routine visual observations on the arc. It has been found to be more convenient, however, to determine the geomagnetic latitudes at which the radio aurorae would intersect the geomagnetic meridian through Halley Bay, on the assumption that the orientation of the radio aurora was the same as that of the corresponding homogeneous arc. (This assumption does not affect the results of the analysis in any way but enables the latitude difference between the equatorwards boundaries of the two phenomena to be determined directly.) These geomagnetic latitudes, for radio aurorae occurring at the centres of each of the range intervals listed in Table II, are given in Fig. 43 as functions of the azimuths of the points of maximum elevation of the corresponding homogeneous arcs.

Clearly, the geomagnetic latitude to which a homogeneous arc must descend to intersect the echoing region depends upon the orientation of that arc. Inspection of Fig. 24 shows that a homogeneous arc must intersect the east limb of the echoing region at a slant range from Halley Bay of less than about 900 km. to have at least 50 per cent probability of being observed by the radar, if it is assumed that the radio echoes are produced by reflection of radio waves from the arcs themselves. For each hour in which only homogeneous arcs were present, the lowest geomagnetic latitude reached by the arcs was noted and the lowest of the range intervals listed in Table II in which radio aurorae were observed gave an upper limit to the geomagnetic latitude to which the radio aurora descended. Discrete and diffuse radio aurorae have been treated separately and structured diffuse radio aurorae have been included on the assumption that these were formed by the simultaneous occurrence of the other two types. The geomagnetic latitude at which radio aurorae in the 900–1,000 km. range interval, orientated parallel to the homogeneous arcs, would

TABLE VI

COMPARISON OF RADIO-ECHO AMPLITUDES AND BRIGHTNESSES OF VISUAL AURORAE

Echo type	*Echo amplitude*	*Brightness of visual aurora*									
		Homogeneous arcs			*Homogeneous bands*			*Rayed arcs and bands*			
		⩽1	>1 ⩽2	*Total*	⩽1	>1 ⩽2	*Total*	⩽1	>1 ⩽2	>2 ⩽3	*Total*
Discrete	No echo	0	0	0	1 (1·41)	1 (0·59)	2	0	0	0	0
	1	3 (2·17)	4 (4·83)	7	1 (1·41)	1 (0·59)	2	1 (0·38)	1 (1·12)	0 (0·50)	2
	2	6 (5·89)	13 (13·11)	19	9 (8·47)	3 (3·53)	12	1 (1·50)	5 (4·50)	2 (2·00)	8
	3	0 (0·93)	3 (2·07)	3	1 (0·71)	0 (0·29)	1	1 (1·12)	3 (3·38)	2 (1·50)	6
	Total	9	20	29	12	5	17	3	9	4	16
Diffuse	No echo	5 (4·03)	8 (8·97)	13	5 (4·94)	2 (2·06)	7	2 (1·31)	4 (3·94)	1 (1·75)	7
	1	2 (1·24)	2 (2·76)	4	3 (2·82)	1 (1·18)	4	0 (0·38)	1 (1·12)	1 (0·50)	2
	2	1 (2·48)	7 (5·52)	8	3 (3·53)	2 (1·47)	5	1 (0·75)	3 (2·25)	0 (1·00)	4
	3	1 (1·24)	3 (2·76)	4	1 (0·71)	0 (0·29)	1	0 (0·56)	1 (1·69)	2 (0·75)	3
	Total	9	20	29	12	5	17	3	9	4	16

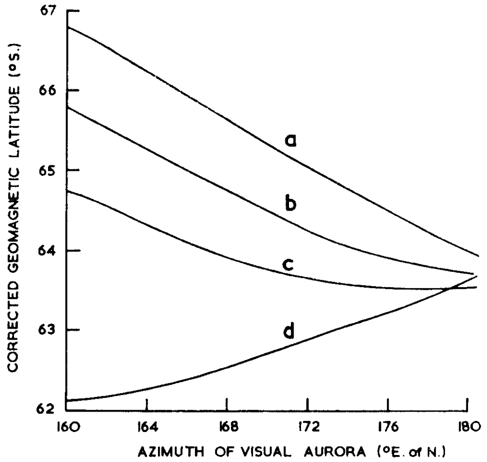


FIGURE 43

The corrected geomagnetic latitudes at which radio aurorae in the range intervals:

a. East limb, 900–1,000 km.,
b. East limb, 700–800 km.,
c. East limb, 500–600 km. and
d. West limb, 500–600 km.

would intersect the magnetic meridian through Halley Bay plotted against the azimuths of the points of maximum elevation of the associated visual aurorae.

have crossed the geomagnetic meridian through Halley Bay, was then subtracted from the lowest geomagnetic latitudes reached by the radio and visual aurorae, calculated as above. In Fig. 44a and b these "relative latitudes" for discrete and diffuse radio aurorae, respectively, have been plotted against the "relative latitudes" of the corresponding homogeneous arcs. The upper limits to the geomagnetic latitudes to which the radio aurorae descended have been plotted as full circles if the observing periods were clear and dark and as open circles if the visual aurora was partially obscured. The vertical bars indicate the uncertainties in the geomagnetic latitudes of the equatorwards boundaries of the radio aurorae. The probable errors arising from uncertainties in the elevations and azimuths of the visual aurorae, typically of order ±0·5° geomagnetic latitude, have not been included in the graphs in the interest of clarity. The numbers of occasions on which the homogeneous arcs were unaccompanied by radio aurorae are shown at the bottoms of the graphs.

If the radio echoes were obtained by direct reflection from the homogeneous arcs, the plotted points should all lie along the dotted lines shown on the graphs. Despite the considerable scatter of the results, it would appear that on average the equatorwards boundaries of both the discrete and diffuse radio aurorae are to be found at a geomagnetic latitude approximately 1° lower than that of the homogeneous arcs. The maximum latitude differences found in clear dark periods were 2·7° and 1·4° for discrete and diffuse radio aurorae, respectively. There is no evidence in these results for different relationships of homogeneous arcs to the two types of radio aurorae when observations are averaged throughout the night as here.

A search has been made for systematic errors which may have produced the observed separation of the phenomena in latitude. These may have arisen through:

i. The assumption that the echoing region was the same as that found by Harrison (1962) during the I.G.Y.
ii. The assumption that the radii of curvature of the homogeneous arcs were those of the circles of geomagnetic latitude on which the arcs lay where they crossed the geomagnetic meridian through Halley Bay.
iii. The assumption that the average height of the bases of homogeneous arcs is 100 km.

Assuming that the echoing region was to remain along a parallel of geographical latitude, it can be shown that a polewards shift of approximately 110 km. in the position of the contour would be required to account for the observed latitude separation of the two phenomena. Because a system of fixed aerials

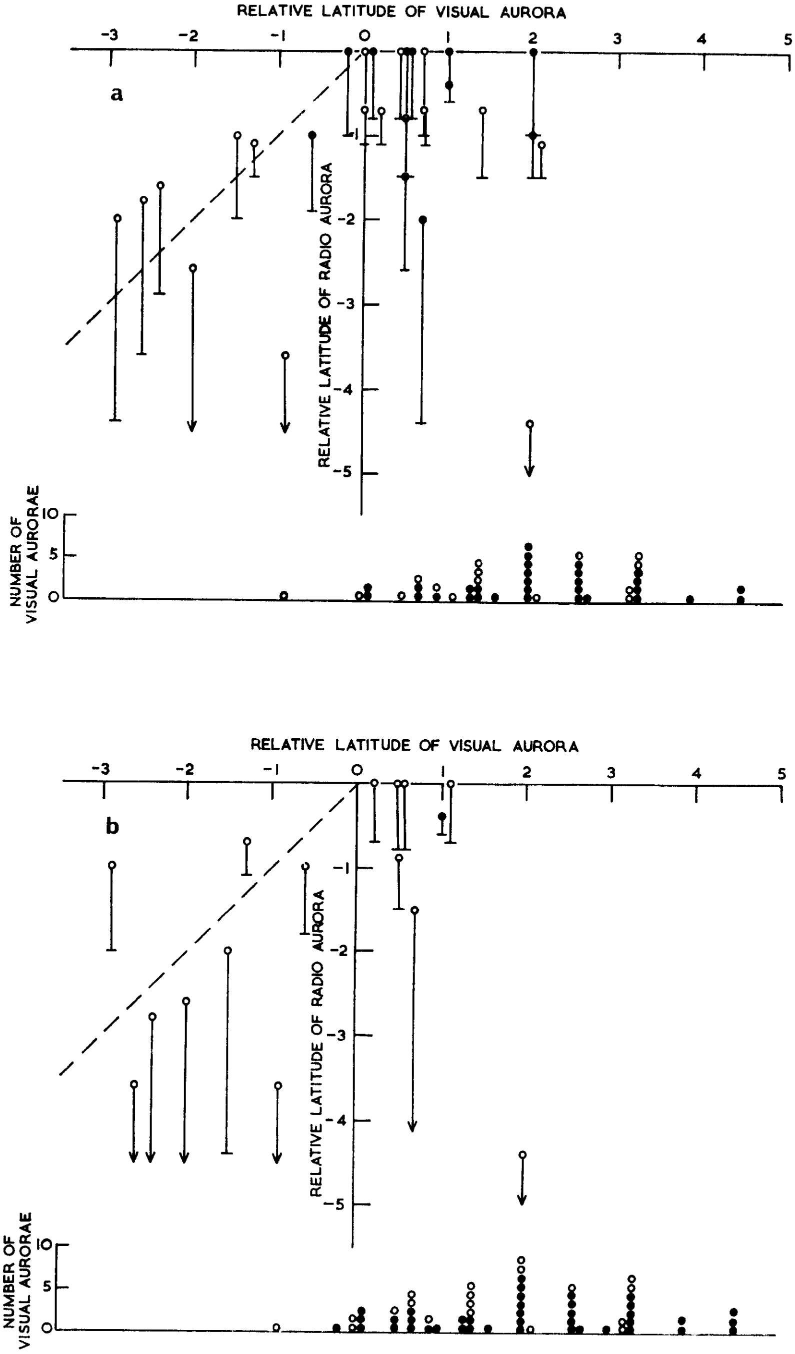


FIGURE 44

Relative latitudes (in degrees) of discrete (a) and diffuse (b) radio aurorae *vs.* relative latitudes of the corresponding visual aurorae.

● Sky clear and dark. ○ Sky partially obscured.

was used at Halley Bay during the I.Q.S.Y., it has only been possible to check the position of the echoing region at its point of closest approach to Halley Bay and evidence was presented on p. 9–11 which showed that there had been no significant change in that position. Assumption (i) is therefore unlikely to have contributed significantly to the observed discrepancy. It can also be shown that it is impossible to account for the discrepancy by choosing any finite radius of curvature for the homogeneous arcs, so that errors introduced through assumption (ii) are also unable to account for the observed separation in latitude.

Taking an elevation angle of 8° to be typical of the homogeneous arcs which accompanied radio aurorae, the heights of the lower borders of the arcs would have to be reduced by about 15 km. to give the required 1° decrease in geomagnetic latitude of the arcs. This implies mean heights as low as or lower than 85 km., so that assumption (iii) could not lead to the observed discrepancy either.

However, the possibility that a combination of systematic errors might account for the discrepancy between the latitudes of the phenomena cannot be excluded. The conclusion that the lower-latitude boundaries of both the discrete and diffuse radio aurorae extend, on average, approximately 1° of geomagnetic latitude equatorwards of the homogeneous arcs must therefore be regarded as tentative. The results presented here are, however, in good agreement with those of Chesnut and others (1968), who found from observations during the course of one night that the echoing regions are located at the edges of visual aurorae, rather than being coincident with them, and are usually displaced between 10 and 100 km. to the north or south of the optical features.

Examination of Fig. 44 shows that the probabilities of observing the radio aurorae were very high when homogeneous arcs intersected the east limb of the echoing region at slant ranges less than about 900 km. and fell very rapidly for arcs beyond that range. Moreover, despite the considerable scatter in the results, it can be seen that the difference in latitude between the two phenomena is almost constant on average. These observations suggest that, although the radio aurorae do not necessarily coincide exactly in space with the homogeneous arcs, they are nevertheless closely associated with them.

4. *Spatial relationships between the radio and visual auroral ovals*

It was found on p. 24–29 that the discrete and diffuse radio aurorae occupy distinct oval zones, the separation of which is greatest during the period 21.00–00.00 U.T. In order to determine which of the two radio-auroral ovals coincides most nearly with the oval of visual aurorae, an examination has been made of their simultaneous latitude distributions during each of the 3 hourly intervals from 21.00 to 06.00 U.T. Outside this period there were too few simultaneous observations of the radio and visual aurorae to give significant results.

As in the previous analysis, it has been necessary to compare visual observations made approximately along the geomagnetic meridian through Halley Bay with radio observations of echoing irregularities at considerable distances from that meridian. Because of the limited data available, it has not been possible to restrict the analysis to periods in which only homogeneous arcs were observed and, since accurate measurements of azimuths were only made for homogeneous arcs, it has been necessary to assume that the orientations of all visual forms included in the analysis show the same diurnal variation as homogeneous arcs. This assumption is probably reasonable on average where arcs and bands are concerned. It is known, in addition, that these forms may extend for thousands of kilometres around the auroral oval so that observations of them on the geomagnetic meridian of Halley Bay will usually indicate whether or not such forms are present at all longitudes covered by the echoing region. Auroral patches and similar forms present problems, however, in that their longitudinal extent may be very limited. The analysis has therefore been restricted to periods in which only arcs or bands were observed.

Sievwright (1969) has shown that the normals to homogeneous arcs observed from Halley Bay move from azimuths of about 160° (geomagnetic south) in the period before local midnight to about 175° at 09.00 U.T. The azimuths of the visual aurorae for each hour were taken from table 2 of Sievwright's (1969) paper and, using the same procedure as in the previous analysis, the mean geomagnetic latitudes at which radio aurorae occurring in the range intervals listed in Table II would cross the geomagnetic meridian through Halley Bay were determined from the graphs of Fig. 43. In determining the latitude distributions only those hourly intervals were considered in which both radio and visual aurorae were observed. Attention was also confined to the months May–August 1965 inclusive, in which visual observations were almost continuous for the period 21.00–06.00 U.T. which is considered here.

Discrete and diffuse radio aurorae were treated separately and structured diffuse echoes were included in the analysis by assuming that these were formed by the simultaneous occurrence of the other two types. The latitude distributions of the radio aurorae were obtained by determining the numbers of occasions on which they were observed in each of the range intervals listed in Table II.

The observations of the visual aurora were classified into 1° intervals of geomagnetic latitude. For each hour the maximum and minimum geomagnetic latitudes at which visual aurorae were observed from Halley Bay were noted and the aurora was assumed to have existed at all points in the intervening region at some time during that hour. The numbers of occasions on which the visual aurorae occurred in each 1° interval of geomagnetic latitude were than determined to give the latitude distributions. A mean height of 100 km. has been assumed for the bases of arcs and bands in determining their geomagnetic latitudes.

The graphs in Fig. 45 show the latitude distributions of both the radio and visual aurorae in each of the 3 hourly intervals from 21.00 to 06.00 U.T. and will now be considered in turn.

The graphs in Fig. 45a provide the most conclusive evidence that, of the two radio-auroral ovals, it is the oval of discrete radio aurorae which shows the closest agreement with the visual auroral oval. It was found on p. 27 that the radio-auroral ovals were most clearly separated in the period 21.00–00.00 U.T. and that separation is also evident here. There is a pronounced peak in the latitude distribution of diffuse radio aurorae at approximately 66° geomagnetic latitude. Unfortunately, the horizon prevented radio observations beyond 68° geomagnetic latitude and there is no evidence of a corresponding peak in the latitude distribution of discrete radio aurorae. The slight peak which can be seen in the distribution corresponds to a maximum in the aerial polar diagram (see Fig. 24). Neither can any reliance be placed on the position of the peak in the latitude distribution of visual aurorae. It must be concluded therefore that the oval of diffuse radio aurorae was to be found, on average, at least 3° of geomagnetic latitude equatorwards of the visual auroral oval at that time of day during the I.Q.S.Y. and that the position of the discrete radio-auroral oval agrees more closely with that of the visual auroral oval. However, the exact relationship between the ovals is far from clear.

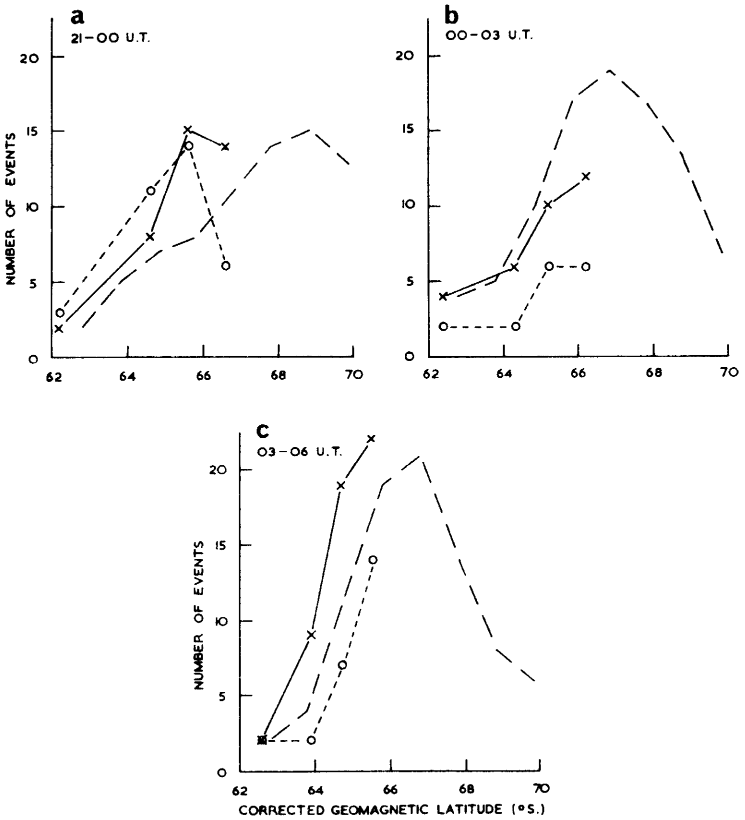


FIGURE 45

Distributions of radio and visual aurorae in corrected geomagnetic latitude.

O– – – –O Diffuse radio aurorae.

X———X Discrete radio aurorae.

— — — Visual aurorae.

During the period 00.00–03.00 U.T., around geomagnetic midnight, all three latitude distributions are similar. When the numbers of occurrences are taken into account, however, the latitude distribution of visual aurorae is seen again to agree much more closely with that for discrete, rather than diffuse, radio aurorae.

After geomagnetic midnight, in the period 03.00–06.00 U.T., the latitude distributions of discrete and diffuse radio aurorae agree equally well with that found for visual aurorae. As noted on p. 27, at this time of day the oval of discrete radio aurorae extends equatorwards of the oval of diffuse radio aurorae.

In summary, these observations suggest that the visual auroral oval agrees more closely in position with the oval of discrete radio aurorae than with that of diffuse radio aurorae. The tendency of both types of radio aurorae to extend equatorwards of the visual aurorae, found earlier on p. 46–50, is also to be seen in Fig. 45.

The results of this analysis support the conclusions of Currie and others (1953). These authors distinguished between diffuse auroral echoes and auroral echoes. Their auroral echoes were characteristically triangular in shape, well defined and possessed a complex fine structure. Of the two types of echo, it was these, which were very similar to the discrete echoes obtained at Halley Bay, that showed a close association with visual aurorae. The results also support the suggestion of Unwin (1966*a*) that his N and M spirals of discrete radio aurorae were closely associated with the oval of visual aurorae. It was shown on p. 32 that Unwin's N and M spirals are equivalent to the oval of discrete radio aurorae. Although several other authors (Forsyth and others, 1960; Leonard, 1962; Bates and others, 1966, 1969) have compared the latitude distributions of radio and visual aurorae and have found them to be closely similar, none has distinguished between different types of radio aurorae in their analyses. Bates and others (1969), however, were of the opinion that their radar did not detect diffuse radio aurorae so that their conclusion, that the positions of the aurora determined from radar and optical data correspond closely, is in agreement with the conclusion reached here.

Unwin and Knox (1968) suggested that the diffuse radio aurora is produced by the Farley instability, whilst the discrete radio aurora is produced directly by the precipitation of energetic particles. Gadsden (1967) has pointed out that the required relative velocity of the ionospheric ions and electrons for the Farley instability to occur can be produced without necessarily increasing the electron density in the regions back-scattering radio waves. Therefore, there need be no increase in optical emission accompanying production of the echoing irregularities although, in general, some particle precipitation and associated optical emission would be expected to accompany the electric fields which produce the ion drift. If the suggestions of Unwin and Knox (1968) are correct, therefore, one would expect the visual aurora to show the closer correspondence with discrete rather than diffuse radio aurorae which has been found here.

It has been shown, however, that the discrete radio aurorae do not occur in exactly the same positions as the visual aurorae but extend equatorwards of them. As noted previously, Chesnut and others (1968) also found that the echoing regions were located at the edges of visual aurorae rather than being coincident with them. These observations, therefore, do not support the suggestion of McDiarmid and McNamara (1969) and McDiarmid (1970) that the radio aurorae are produced by ion-acoustic waves occurring within a band of enhanced ionization embedded in the ionospheric plasma. They suggested that the ion-acoustic waves are generated by currents which flow across the bands of enhanced ionization and close in the outer magnetosphere after flowing along magnetic field lines at the edges of the bands. The necessary electric fields orthogonal to the magnetic field lines would have to act parallel to the bands, however, and recent direct measurements of electric fields in the ionosphere (Westcott and others, 1969) have shown that these are directed towards auroral forms. In addition, the electric fields were found to be sufficiently intense to excite ion-acoustic waves in the regions outside the auroral forms but were very weak within the forms themselves. The observations do, however, support the suggestion of Unwin and Knox (1971) that a second type of plasma instability, which they have called the "drift-gradient instability" may be used to explain many features of the discrete radio aurorae. The growth of this instability requires the existence of a positive gradient of ionization density in the direction of the electric field and would be most likely to occur at the edges of regions of electron precipitation.

Feldstein (1969) has emphasized the importance of information on the position of the auroral oval to studies of the structure of the magnetosphere and has suggested that multiple-frequency sounding of the type used by Bates and his co-workers (e.g. Bates and others, 1966) appears at present to be the most reliable radar method of determining the oval's position. The results of this section suggest that, if a distinction between echo types is possible, observations of the discrete radio aurora should be used to determine the position of the visual auroral oval, particularly in the evening period.

IX. ASSOCIATION OF RADIO AURORAE WITH OTHER IONOSPHERIC PHENOMENA

1. *Introduction*

Ideally, in any study of the relation of the radio aurora to other ionospheric phenomena, an ionosonde should be stationed directly beneath the region in which the radio aurora is commonly observed. Unfortunately, such an ionosonde was not available during the I.Q.S.Y. At its closest point, the echoing region was still at a slant range of 300 km. from the nearest ionosonde, which was that at Halley Bay, and most of the radio aurorae observed were at much greater ranges than this, in the range interval 500–1,100 km., as shown by Fig. 24.

The large separation of the regions of observation automatically reduces the certainty with which conclusions may be drawn from the analysis which follows. The situation, however, is not quite as bad as it might at first appear. To a first approximation, for distances of the order involved here, those phenomena which are produced by the precipitation of charged particles into the Earth's atmosphere are known to be extended along lines of geomagnetic latitude (e.g. Chamberlain, 1961) and the corrected geomagnetic latitude of the west limb of the echoing region differs only by 1° from that of Halley Bay (Fig. 7). The appearance of radio aurora on the west limb of the echoing region therefore probably implies that radio aurora was also overhead at Halley Bay.

In the following analysis the various ionospheric phenomena are examined, where possible, for three different distributions of the radio aurora. These are listed in Table VII together with the corresponding lower limits to the corrected geomagnetic latitudes at which the radio aurora occurred (or may have occurred in the case of the highest latitude interval). This technique has revealed the behaviour of various ionospheric phenomena within three broad belts, which are approximately fixed in position with respect to the radio-auroral oval, one belt being coincident with, and the other two lying equatorwards of this oval.

TABLE VII

MINIMUM LATITUDES OF SELECTED RADIO-AURORAL DISTRIBUTIONS

Distribution of the radio aurora	*Minimum corrected geomagnetic latitude of the radio aurora*
None observed	$>69°$ (possibly)
Present on east limb only	$>64°$
Present on west limb	$<63°$

2. *Association of radio aurorae with sporadic E*

Thomas (1960) studied the distribution of the auroral zone E_s, including only values of $f_oE_s \geqslant 5 \cdot 0$ MHz or $fE_s \geqslant 5 \cdot 8$ MHz, and found that at a given Universal Time there is a tendency in each hemisphere for E_s to occur along a curve extending from the region of the magnetic poles to lower latitudes with a gradual increase of easterly longitude. Two curves or "spirals" of this type, derived for different kinds of E_s, are included in Fig. 31 where their relationship with the auroral oval is apparent. Clearly, the rotation of the E_s spirals around the geomagnetic poles towards earlier hours as magnetic disturbance increases (Thomas, 1962) is associated with the expansion of the auroral oval which occurs under these conditions.

In this section the statistical relationships between the radio aurora and sporadic E at Halley Bay are examined, the different E_s types being at first combined and then treated individually.

By definition, it is impossible to observe the normal ionospheric reflections when black-out is present. and at such times it is therefore impossible to know whether E_s is present or not. Following Bellchambers and Piggott (1960), the rates of incidence have therefore been expressed as percentages of the time when normal ionospheric reflection was possible.

The probability of observing any E_s for each of the three radio-auroral distributions listed in Table VII proved to be time dependent as shown in Fig. 46 where winter (May–August) and summer (October–December) periods have been treated separately. The equatorwards movement of the radio-auroral oval

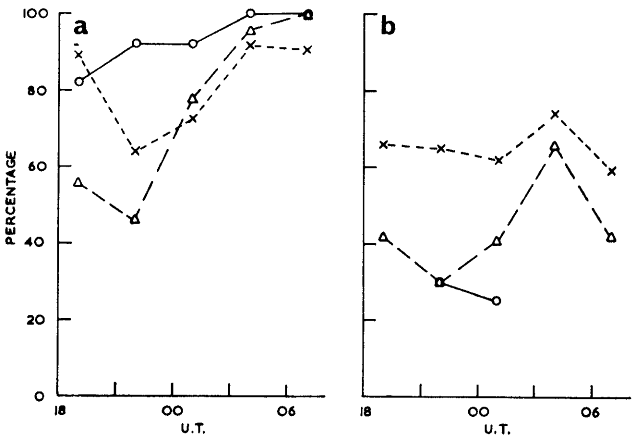


FIGURE 46

Diurnal variations in the probability of observing E_s in (a) winter (May–August) and (b) summer (October–December) for the following distributions of radio aurorae:

×– – – –× No radio aurora.
△— — — △ East limb only.
○———○ West limb.

to a position such that it intersected the east limb of the echoing region was accompanied by a large decrease in occurrence of E_s during the evening in both seasons and for the remainder of the night during summer. In the winter midnight and morning periods the probability of observing E_s increased. The further movement of the radio aurora to the west limb of the echoing region was associated with an increase in occurrence of E_s during the winter. What little data are available suggests that a similar recovery in E_s occurrence did not take place during the summer.

Variations in the ordinary wave top frequency, f_0E_s, closely followed the variations in occurrence of E_s. In Table VIII the occurrence of hourly values of f_0E_s in each of three classes is compared with the

TABLE VIII

RELATIONSHIP BETWEEN RADIO AURORA AND f_0E_s FOR MAY–AUGUST 1965

21–23 U.T.

Radio-auroral distribution	f_0E_s (MHz)			*Total*
	<1·5 or no E_s	1·5–3·0	>3·0	
None	158 (78·3)	30 (14·8)	14 (6·9)	202
East limb only	74 (92·5)	6 (7·5)	0 (0·0)	80
West limb	8 (44)	7 (39)	3 (17)	18

03–05 U.T.

Radio-auroral distribution	f_0E_s (MHz)			*Total*
	<1·5 or no E_s	1·5–3·0	>3·0	
None	153 (64·1)	68 (28·6)	17 (7·3)	238
East limb only	29 (43·9)	29 (43·9)	8 (12·2)	66
West limb	2 (18)	5 (46)	4 (36)	11

distribution of radio aurorae for winter evening and morning periods. Percentage occurrences are shown in brackets. In the evening the variation of f_0E_s was bimodal, at first decreasing, then increasing as the radio auroral oval approached Halley Bay. In the morning the equatorwards movement of the radio aurora was associated with a gradual increase in the value of f_0E_s.

The classification of E_s types adopted by the World Wide Soundings Committee (Piggott and Rawer, 1961) depends upon the appearance of the E_s traces on ionograms and results in certain anomalies. Thus "thin-layer" traces are classified as h type (high) if they appear above the maximum of the E layer; c type (cusp) at the maximum, and l type (low) below the maximum of the E layer. When, at night, no regular E layer is present, the above types are merged to form a single type f (flat). As pointed out by Smith (1961), this is more a matter of compartmentalization of the E_s in terms of height and time than is the case with the types more or less unique to the auroral zone. These are the a type (auroral), r type (retardation) and s type (slant). Together with a type of flat E_s also found in the auroral zone, these are distinct from other types of E_s in that they are closely associated with magnetic activity (Appleton and others, 1937) and with auroral activity (e.g. Knecht, 1956; Bates, 1961; Hunsucker and Owren, 1962).

The set of graphs comprising Fig. 47 covers each of the E_s types commonly occurring at Halley Bay, and were obtained by following exactly the same procedure as that used to obtain Fig. 46. These graphs will now be discussed in turn.

During the I.Q.S.Y., flat E_s was negatively correlated with radio aurora on the whole. The probability of observing this type of E_s, which was by far the most common E_s type during the winter at Halley Bay, increased throughout the night in a manner almost independent of the distribution of radio aurorae. It was the behaviour of flat E_s which was mainly responsible for the winter evening decrease in occurrence of E_s at Halley Bay when the radio aurora appeared on the east limb of the echoing region.

There is now considerable evidence to suggest that one type of flat E_s occurring at high latitudes differs from that found in the temperate zone. Bellchambers and Piggott (1960) found that the incidence of flat

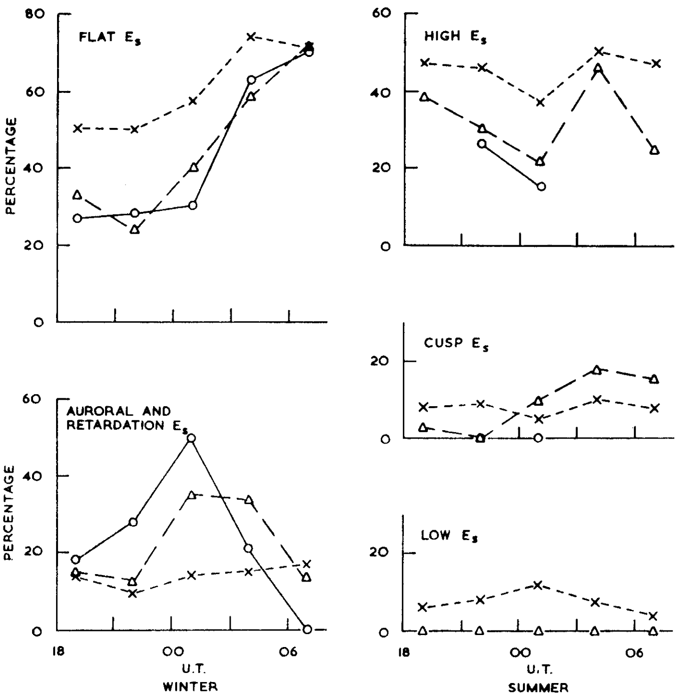


FIGURE 47

Diurnal variations in the probabilities of observing various types of E_s in the winter and summer periods for the following distributions of radio aurorae:

×- - - -× No radio aurora.
△— — —△ East limb only.
○———○ West limb.

E_s occurring at Halley Bay during the I.G.Y. was bimodal, at first decreasing with rising magnetic activity and then increasing again. This behaviour, they pointed out, would be expected if the flat E_s at Halley Bay was made up of a mixture of the classical high-latitude storm E_s and typical temperate-latitude E_s. Schaeffer (1967*a*) was able to distinguish the temperate-zone flat E_s occurring at Mawson, close to the polewards edge of the southern auroral zone, from another type which tended to precede local auroral events.

Bellchambers and Piggott (1960) found that most of the flat E_s occurring in the midnight maximum period was positively correlated with the local magnetic *Q* index, whilst most of that occurring outside that period was found to be negatively correlated. To some extent, however, the behaviour in each of these periods was still bimodal. In Fig. 47 there is some evidence for bimodal behaviour of the flat E_s in the periods 21–23 and 03–05 U.T. This last period contains the maximum in occurrence of flat E_s, in agreement with the results of Bellchambers and Piggott (1960). There is some evidence, then, that when radio aurora was present on the west limb of the echoing region (so that it was probably also present above Halley Bay) the flat E_s component of the high-latitude storm E_s tended to be observed. It has not been possible, however, to separate out this type of E_s for further study. An association between flat E_s and visual aurora was reported by Hunsucker and Owren (1962).

Auroral E_s was first distinguished by Knecht (1956), who found that there was a strong tendency for this type of E_s to be recorded when the visual aurora was present near the zenith and that there was a direct relationship between the brightness of the aurora and the top frequency of the E_s. Hunsucker and Owren (1962) confirmed these results but pointed out that auroral E_s was only one of two types which were associated with visual aurora in the zenith, the other type being flat E_s. Auroral E_s is predominantly a night-time phenomenon with maximum occurrence at about 01.00 U.T. at Halley Bay during the I.G.Y. (Bellchambers and Piggott, 1960). Its maximum occurrence "spiral" is shown in Fig. 31.

Retardation E_s was much less common than auroral E_s at Halley Bay during the I.Q.S.Y. The maximum occurrence "spiral" of retardation E_s is shown in Fig. 31 at a lower latitude than that of auroral E_s. At Halley Bay, however, the two types show similar behaviour and incidence (Bellchambers and Piggott, 1960). Following these authors, the two types have been grouped together here as a single parameter.

Auroral and retardation E_s, occurring in the late evening and midnight periods at Halley Bay during winter, were positively correlated with radio aurora. After midnight the probability of observing these E_s types was greatest when the radio aurora was observed only on the east limb of the echoing region and decreased sharply as the radio aurora moved closer to the base. Obscuration of the E_s by increased absorption, which was associated with radio aurora on the west limb at these times, may be invoked to explain some of the observed decrease but an examination of all of the available data has suggested that most of the decrease is real. As the radio aurora moved close to Halley Bay in the morning, any auroral E_s present tended to disappear from the ionograms to be replaced by flat E_s.

Auroral and retardation E_s were rare during the summer months but their occurrence tended to be associated with the occurrence of radio aurora as in the winter months.

High E_s present in the summer was negatively correlated with radio aurora which is to be expected in view of its correspondence with the winter flat E_s and its negative correlation with magnetic disturbance at Halley Bay (Bellchambers and Piggott, 1960).

Cusp E_s, on the other hand, was negatively correlated with radio aurora in the evening and positively correlated in the midnight and morning periods. These observations contrast with the negative correlation with magnetic disturbance which this type displayed during the I.G.Y. (Bellchambers and Piggott, 1960). These authors, however, did not split up the cusp E_s on a time basis in obtaining their result.

Low E_s occurred mainly in quiet periods when no radio aurora was observed. In fact, this type was never observed when radio aurora was present on the east limb of the echoing region and was observed on only two occasions on which radio aurora was observed on the west limb.

Slant E_s and the new type "d" E_s, which consists of very low stratification giving generally weak ionogram traces below about 90 km. (Piggott and Rawer, 1961), were occasionally observed at Halley Bay, mainly during the winter months. The occurrences of these E_s types and radio aurora are compared in Table IX. The numbers in brackets give the expected occurrence frequencies derived on the hypothesis that the association between the radio aurora and these two ionospheric phenomena was purely random. It is clear that both types of E_s tend to be associated with the occurrence of radio aurora close to Halley Bay. This result for slant E_s is in agreement with that of Bates (1961), who also found that in general the

TABLE IX

ASSOCIATION OF RADIO AURORAE WITH "slant" AND TYPE "d" E_s

Radio-auroral distribution	*Slant E_s*		*Type "d" E_s*		*Total*
	Present	*Absent*	*Present*	*Absent*	
None	2 (6·8)	1,269 (1,264·2)	8 (23·3)	1,263 (1,247·7)	1,271
East limb only	0 (1·5)	280 (278·5)	4 (5·1)	276 (274·9)	280
West limb	7 (0·7)	136 (142·3)	19 (2·6)	124 (140·4)	143
Total	9	1,685	31	1,663	1,694

range of the high-frequency end of the slant E_s echo, when this extended beyond 23 MHz, was the same as that of a 41 MHz radio-auroral echo observed simultaneously.

3. *Association of radio aurorae with spread F*

Direct HF radar reflections from field-aligned irregularities in the F region of the ionosphere were first reported by Peterson and others (1955) and showed the rapid fading characteristic of the E-region radio-auroral echoes. Baldwin (1960) and Hower and Makhijani (1969) have shown that there is a close correlation between the F-region echoes and spread-F echoes on ionograms provided that the ionospheric sounder is located very close to the back-scattering region. In cases where this condition is not satisfied, the correlation has been found to be poor (Peterson and others, 1955; Baldwin, 1960) as would be expected in view of the latitudinal variation in occurrence of spread F.

TABLE X

RELATIONSHIP BETWEEN THE OCCURRENCE OF RADIO AURORA AND SPREAD F

21–00 U.T.

	Spread F absent	*Spread F present*	*Total*
Radio aurora absent	90 (96·2)	81 (74·8)	171
Radio aurora present	67 (60·8)	41 (47·2)	108
Total	157	122	279

03–06 U.T.

	Spread F absent	*Spread F present*	*Total*
Radio aurora absent	130 (129·5)	42 (42·5)	172
Radio aurora present	38 (38·5)	13 (12·5)	51
Total	168	55	223

The tendency of spread F to occur overhead at Halley Bay when E-region radio aurorae were observed is examined in Table X, where evening (21.00–00.00 U.T.) and morning (03.00–06.00 U.T.) periods are treated separately. Unfortunately, when radio aurora was present on the west limb of the echoing region, so that it was likely to be overhead at Halley Bay, the F region was frequently not observable and it has been necessary to include all observations of radio aurorae in this analysis, whatever their locations. The required information concerning the occurrence of spread F was drawn from the hourly tables of ionospheric data for the months May–August 1965 inclusive. Only those hours in which the F region was observed, and in which the radio-auroral radar was operating satisfactorily, were included in the analysis. The numbers in brackets in the contingency tables give the expected occurrence frequencies calculated on the hypothesis that the association between the two phenomena is purely random. Application of the χ^2 test reveals that the observed and predicted distributions are not significantly different, and it must therefore be concluded that there is no significant association between the radio aurora observed from Halley Bay and spread F observed overhead at Halley Bay.

The lack of association found here between these two phenomena may of course arise from the large distance between the regions of observation, on average about 700 km. Over distances of this order, little association has been found between the direct back-scatter echoes from the E- and F-region irregularities (Peterson and others 1955; Baggaley, 1967).

4. *Association of radio aurorae with auroral absorption*

The anomalous absorption of radio waves which occurs at high latitudes was discovered during the International Polar Year, 1932–33 (Appleton, 1932). Since that discovery, several categories of anomalous absorption have been identified, the most important being auroral absorption (AA) and polar-cap absorption (PCA). There were no PCA events at Halley Bay during the I.Q.S.Y. (personal communication from W. R. Piggott). Sudden cosmic noise absorption events (SCNA) are caused by solar X-ray emission and are confined to the sunlit hemisphere. Sudden commencement absorption events (SCA) are found only in the auroral zones but are generally too short-lived to be detected in routine quarter-hourly ionospheric soundings. AA events are therefore the only type which need be considered in the analysis which follows, where most attention is paid to night-side events in the polar winter.

Studies of AA using ionosondes (Agy, 1954; Cox and Davies, 1954) have shown that the diurnal maxima in the occurrence of ionospheric black-outs occur later with increasing latitude. Thomas and Piggott (1960) showed, in addition, that at a given Universal Time the maxima of black-out occurrence are to be found along a spiral curve extending to higher latitudes with increasing easterly longitude. Such a curve, plotted in dipole latitude and time coordinates, is shown in Fig. 31 and lies close to the morning side of the auroral oval. The absorption found along the morning side of the oval is rather weak and is not normally detected by riometers, which are less sensitive to absorption than ionosondes. Statistical studies using riometers have demonstrated instead the existence of a zone of intense AA which has circular symmetry in a geomagnetic latitude–geomagnetic time coordinate system, being at about the same latitude on the day and night sides of the Earth (e.g. Hartz and others, 1963; Hook, 1968). The peak of this AA zone lies about 2° equatorwards of the peak of the visual auroral zone so that at the diurnal maximum in occurrence of AA at about 09.00 L.T. the peak of the AA zone lies about 10° equatorwards of the visual auroral oval.

The analysis described here has been based on the values of $f_{\text{min.}}$, the lowest frequency at which radio waves were reflected from the ionosphere, given in the monthly tables of ionospheric data and on F plots. Studies of AA based on the values of $f_{\text{min.}}$ and the occurrence of black-out are usually complicated by a number of factors. In particular, the absorption intensity required to produce black-out will depend on the critical frequencies of the ionospheric layers, factors which themselves have important temporal variations, whilst the values of $f_{\text{min.}}$ are dependent on equipment sensitivity. Bellchambers (1967) has asserted, however, that the effects of these complications are not serious where the Halley Bay data are concerned. At Halley Bay, high sensitivity of the ionosonde was obtained down to 0·7 MHz through the use of large aerials, and changes in $f_{\text{min.}}$ therefore detected only large changes in absorption. Bellchambers has scrutinized all of the no-echo events at Halley Bay during the I.Q.S.Y. and has concluded that not more than 1 per cent of the black-outs recorded could be the result of the lack of ionization in the E and F regions.

The probabilities of $f_{\text{min.}}$ exceeding 1 MHz in the winter and summer periods and of observing ionospheric black-outs during the winter period, for each of the three radio-auroral distributions previously mentioned, are given in Fig. 48. Clearly, these probabilities are highly time dependent.

Under quiet conditions, when no radio aurora was observed, the probability of $f_{\text{min.}}$ exceeding 1 MHz was slightly higher during the summer than during the winter. This difference between the incidence of absorption in the two seasons is most apparent around 18.00 U.T. As noted by Bellchambers and Piggott (1960), a secondary peak in the incidence of absorption occurred at about 22.00 U.T. in the winter months but not in the summer.

When radio aurora was observed on the east limb of the echoing region, the probability of $f_{\text{min.}}$ exceeding 1 MHz increased relative to its value under quiet conditions and was lower near midnight than during the morning or evening periods. (The decreased probability noted at 01.00 U.T. during the summer is not statistically significant.) Again, the incidence of $f_{\text{min.}}$ values over 1 MHz was greater in summer than in winter.

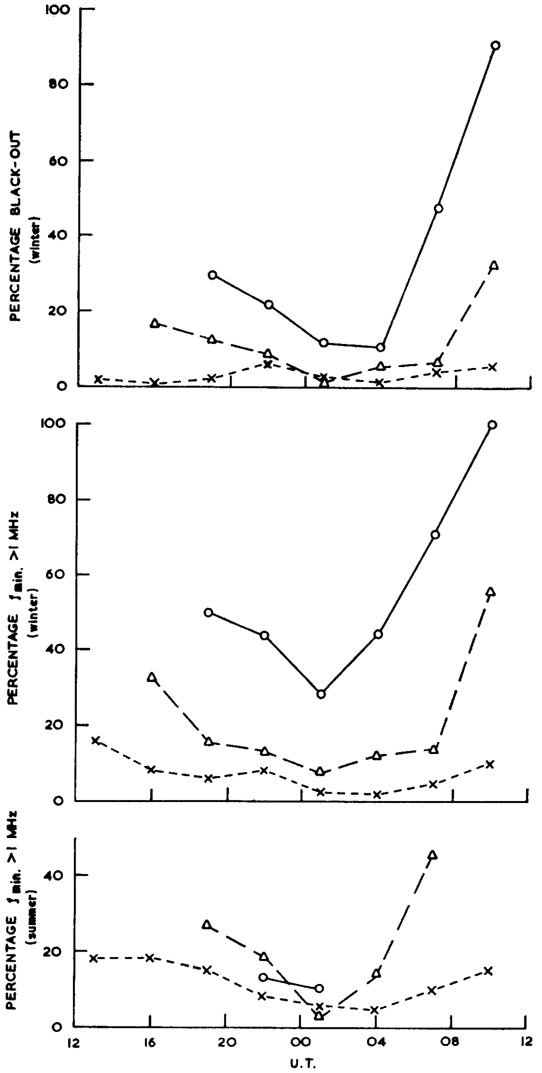


FIGURE 48

Diurnal variations in the probability of occurrence of ionospheric black-out and values of $f_{\text{min.}}$ greater than 1 MHz for three distributions of radio aurorae:

× – – – – × No radio aurora.
△ ——— △ East limb only.
○ ——— ○ West limb.

Winter included the months May–August 1965, and summer the months October–December 1965.

The movement of the radio aurora equatorwards to the west limb of the echoing region, so that it was probably overhead at Halley Bay, was accompanied by a very large increase in the probability of $f_{\text{min.}}$ exceeding 1 MHz during the winter but no similar increase occurred during the summer. In both seasons the diurnal variation closely resembled that found when radio aurora was present only on the east limb.

The results described here for those cases where the radio aurora did not advance beyond the east limb of the echoing region are in good agreement with those of Bellchambers and others (1962), who found an occurrence maximum of absorption during the summer at Halley Bay. However, it would seem that, whilst this behaviour is shown by absorption occurring at some distance from the radio-auroral oval, that found close to the oval maximizes in the winter months.

Ionospheric black-outs which occurred during the winter months were related to the radio aurora in essentially the same manner as were absorption events with $f_{\text{min.}}$ in excess of 1 MHz (Fig. 48). Comparison of their peaks at 22.00 U.T. shows that the absorption occurring at that time was intense, about 75 per cent of the absorption events with $f_{\text{min.}}$ over 1 MHz being, in fact, sufficiently intense to produce the black-out condition. Similarly, the morning absorption events were generally intense, whilst those occurring around and shortly after local midnight were generally weak.

Bellchambers and Piggott (1960) found that, except for a short period in the evening, the probability of black-out occurring increased rapidly with local magnetic activity. At first sight, therefore, it would appear to be possible to explain qualitatively many of the features of Fig. 48 without assuming any direct association between radio aurorae and auroral absorption. Thus, for radio aurora to be observed first on the east limb and then on the west limb of the echoing region requires increasingly higher levels of magnetic disturbance which would also increase the probabilities of black-out occurrence. Similarly, the magnetic disturbance levels required before radio aurorae are observed are much higher in the early afternoon and late morning than at midnight, so that higher probabilities of black-out occurring would also be expected at these times. The following analysis, however, shows that the actual behaviour is much more complex than this.

Two periods, 03.00–09.00 U.T. and 19.00–00.00 U.T. in the months May–August inclusive, have been selected for more detailed study. In Fig. 49 the probabilities of observing black-out during these periods

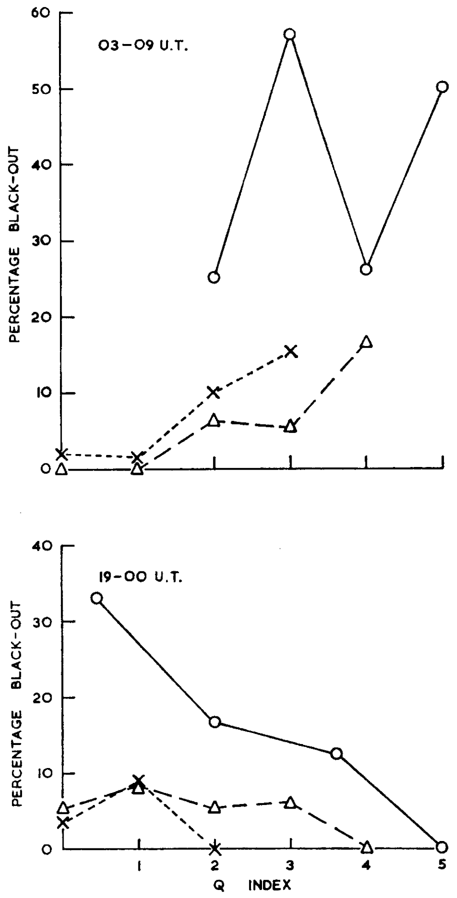


FIGURE 49

The probability of observing ionospheric black-out at each level of magnetic disturbance for the following distributions of radio aurorae:

×- - - -× No radio aurora.
△— — —△ East limb only.
○———○ West limb.

have been determined as functions of the local magnetic *Q* index for three different radio-auroral distributions.

In the morning period, 03.00–09.00 U.T., the incidence of black-out was, on the whole, positively correlated with magnetic activity. With the approach of the radio-auroral oval towards Halley Bay, however, the incidence of black-out at first decreased and then increased again to a high value when the radio aurora reached the vicinity of the station. It seems likely that the absorption observed in the absence of radio aurorae in this period belonged to the circular zone of auroral absorption which has been intensely studied by means of riometers. This moved equatorwards as the radio aurora approached Halley Bay to be replaced by absorption associated with the auroral oval. This latter type of absorption was very common when radio aurora was present on the west limb of the echoing region. The sharp minimum which occurred when the local *Q* index equalled 4 is significant at the 5 per cent level by the χ^2 test and suggests that two mechanisms may have been operative, at different levels of magnetic activity, in producing the absorption in this region. Diffuse radio aurorae tended to appear on the west limb at these times when the *Q* index exceeded 4 but no association has been found between these radio aurorae and the absorption produced at high levels of magnetic disturbance.

In the evening period, 19.00–00.00 U.T., black-outs occurred mainly at times of weak magnetic disturbance, in agreement with the conclusions of Bellchambers and Piggott (1960). Bellchambers (1967) emphasized that these absorption events were real and pointed out that they tended to follow periods of high magnetic disturbance within 12 hr. There is some evidence in Fig. 49 that the incidence of black-out was slightly increased when radio aurora was present on the east limb of the echoing region. Again, however, the incidence of black-out rose sharply with the appearance of radio aurora on the west limb of the echoing region.

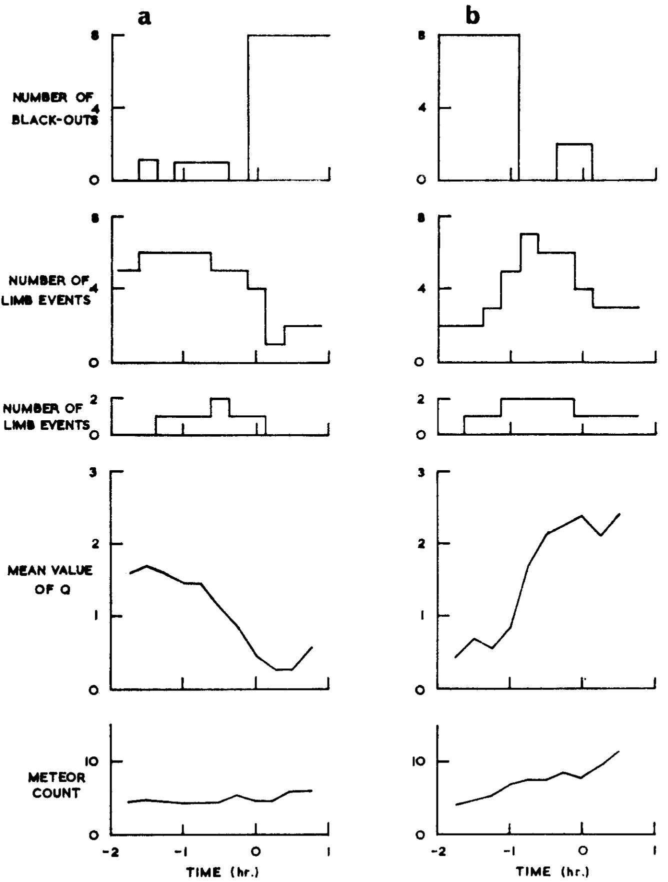


FIGURE 50

Superposed epoch analysis of various phenomena occurring in the evening at Halley Bay in the months May–August 1965. Times are measured from (a) the beginning and (b) the end of periods of ionospheric black-out.

The association of evening black-outs with both periods of weak magnetic disturbance and radio aurorae, which show a strong positive correlation with magnetic activity, is very striking and is examined in more detail in Fig. 50. Inspection of the *f*-plots for the months May–August 1965 inclusive enabled eight evenings to be selected during which black-outs lasting more than 1 hr. occurred in periods of weak magnetic disturbance. Two superimposed epoch analyses (Fig. 50) were then carried out, taking the times at which the black-out started and ended as the zeros of time in Fig. 50a and b, respectively. The commencement of black-out was accompanied by disappearance of the radio aurorae from the whole of the echoing region and by a decrease of the local magnetic activity as represented by the *Q* indices for Halley Bay. At the end of the period of black-out the radio aurorae re-appeared and the magnetic activity at Halley Bay increased rapidly. That the disappearance of the radio aurorae was not due to absorption of the 71·3 MHz radio waves is demonstrated by the absence of any comparable changes in the meteor rates at those times. The gradual increase of the meteor rate with time in Fig. 50b is due to the normal diurnal variation in the meteor rate. The changes in the occurrence of radio aurorae were more gradual than the changes in the incidence of black-out so that the periods in which they occurred tended to overlap to some extent. This accounts for the association between these phenomena found in the previous statistical analysis, although in fact there is a very marked anti-correlation between them.

The deceleration which the electrons responsible for this absorption experience on entering the Earth's atmosphere results in the production of X-rays which have been observed at balloon altitudes (Barcus and Rosenberg, 1966). The energy spectra of the X-rays resulting from these impulsive bursts were found to be principally hard, with *e*-folding energies of 30–50 keV. These authors suggested that the observed *bremsstrahlung* X-ray spectra represent a good semi-quantitative indication of the primary electron spectra over the range 50–250 keV.

It is possible to explain the observations presented in Fig. 50 if it is assumed that the ionospheric absorption is produced by the hardening of the energy spectra of the electrons responsible for the radio aurora. Under these circumstances the flux of low-energy electrons would necessarily decrease. Computations of ionization profiles by Rees (1963) and Berger and others (1970) show that the ionization produced per incident electron will decrease with increasing particle energy at any given height provided that this height is always at or above that at which the lowest-energy electrons produce maximum ionization. The reduction in the flux of low-energy electrons and in the ionization produced at the 110 km. level by the electrons when energized will result in the loss of the radio-auroral echoes. The reduced ionization in this region will also result in a reduction of the flow of ionospheric currents, so that the local magnetic disturbance will also become smaller.

A peculiar feature of these evening absorption events is that the associated ionospheric absorption as measured by riometers is characteristically low (Barcus and Brown, 1966; Schaeffer, 1967*b*) and at least 2–10 times lower than that commonly observed with other X-ray events of comparable intensity. There is evidence to suggest that at altitudes below 70 km. the night-time detachment of electrons from negative ions is negligible (McDiarmid and Budzinski, 1964), and Barcus and Brown (1966) have pointed out that this will result in a large effective re-combination coefficient and thus in a reduced electron density at these altitudes. This will have little effect upon absorption estimates for particle spectra with *e*-folding energies below 20 keV, since the main contribution to absorption at 30 MHz from such particles comes from heights above about 80 km., where negative ion considerations are relatively unimportant. However, the more energetic electrons responsible for the evening absorption events discussed here will produce maximum ionization at lower heights where the increased effective re-combination coefficient will reduce the electron densities and therefore the absorption produced. Although the absorption is only weak when observed by riometers, it is still sufficiently intense to produce complete ionospheric black-out owing to the great sensitivity of the ionosonde to absorption.

There has been in recent years considerable disagreement between various authors as to the correct form of the diurnal variation in the electron energy spectrum. Bewersdorff and others (1966), from observations of X-rays with energies over 20 keV, inferred a hardening of the spectrum between 01.00 and 17.00 hr. L.T. and a softening between 21.00 and 01.00 hr. Barcus and Rosenberg (1966) found that the energy spectrum in the range 50–150 keV was hardest before auroral break-up, as previously discussed. Johansen (1965) derived a linear relation between the intensity of cosmic noise absorption, *A*, and the square root of the auroral luminosity, *I*. The parameter $R=A/I^{\frac{1}{2}}$ is independent of the electron flux and depends only on the energy of the incident electrons. By assuming that the value of *R* increased with the hardness of the electron-energy spectrum, Johansen (1965) found that the spectrum hardened between 20.00 and 23.00 M.E.T. with maximum hardness between 22.00 and 23.00 M.E.T. Results obtained by Berkey (1968), using the same technique, suggest that the energy spectrum hardens continuously from about 20.00 to 06.00 150° W.M.T. In the previous discussion, however, it was shown that electrons with *e*-folding energies of 30–50 keV generally produce both little luminosity and little absorption, so that the parameter *R*, after first increasing to a maximum value for some particle energy, will become small again for these higher energies. The interpretation of low values of *R* will therefore be ambiguous and it is felt that this will largely account for the disagreement concerning the form of the diurnal variation in electron-energy spectra. The observations reported here support the view that the electron-energy spectrum has minimum hardness near local midnight and maximum hardness during the evening, at 19.00–20.00 30° W.M.T. at Halley Bay.

It has been shown that the evening absorption events, when observed overhead at Halley Bay, were associated with radio aurorae on both limbs of the echoing region. Assuming that these radio aurorae were on average at ranges of about 700 km. on both limbs of the echoing region and that the absorbing regions are extended along parallels of corrected geomagnetic latitude, these observations suggest that the latitudinal and longitudinal extents of the absorbing regions were at least about 500 and 700 km., respectively. The region of precipitation must therefore be greatly increased during these events.

X. METEOR ACTIVITY

HOURLY sums of the meteor-echo counts were derived and tabulated as described on p. 9. The diurnal variation in the meteor-echo rate was derived from the tables for each 3 monthly period, the results being

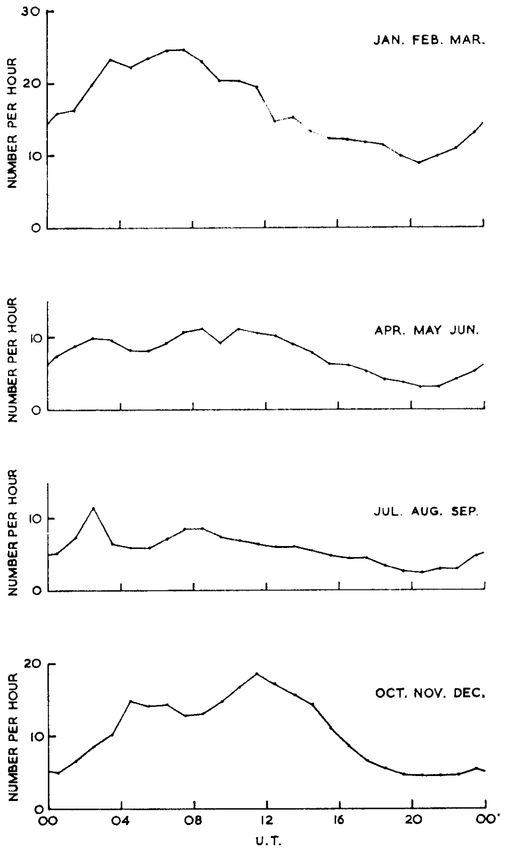


FIGURE 51

The diurnal variation in meteor radio-echo rate. The upper curve was derived from observations on the south rhombic antenna, the remainder from observations on the south-east rhombic antenna.

shown in Fig. 51 as the mean number of echoes per hourly period. The graph for January–March 1965 was derived from observations made with the south aerial commencing 20 January. The remaining graphs were derived from observations made with the south-east rhombic which commenced on 11 April. There is a local time difference between the meteor-echo regions surveyed by these two aerials, the local time at the south-east region preceding that at the south region by approximately 1 hr.

Shower activity is evident in the graphs for July–September and October–December. The sharp peak at 02–03 hr. U.T. in the graph for July–September is due largely to the δ-Aquarid shower which is active in late July. The existence of a large summer peak in the radio-echo meteor rate at Halley Bay was suggested by Harrison (1962). Its existence was also suggested by Weiss and Smith (1960), observing from Adelaide, Australia, and was confirmed by Ellyett and Keay (1963), observing from Christchurch, New Zealand.

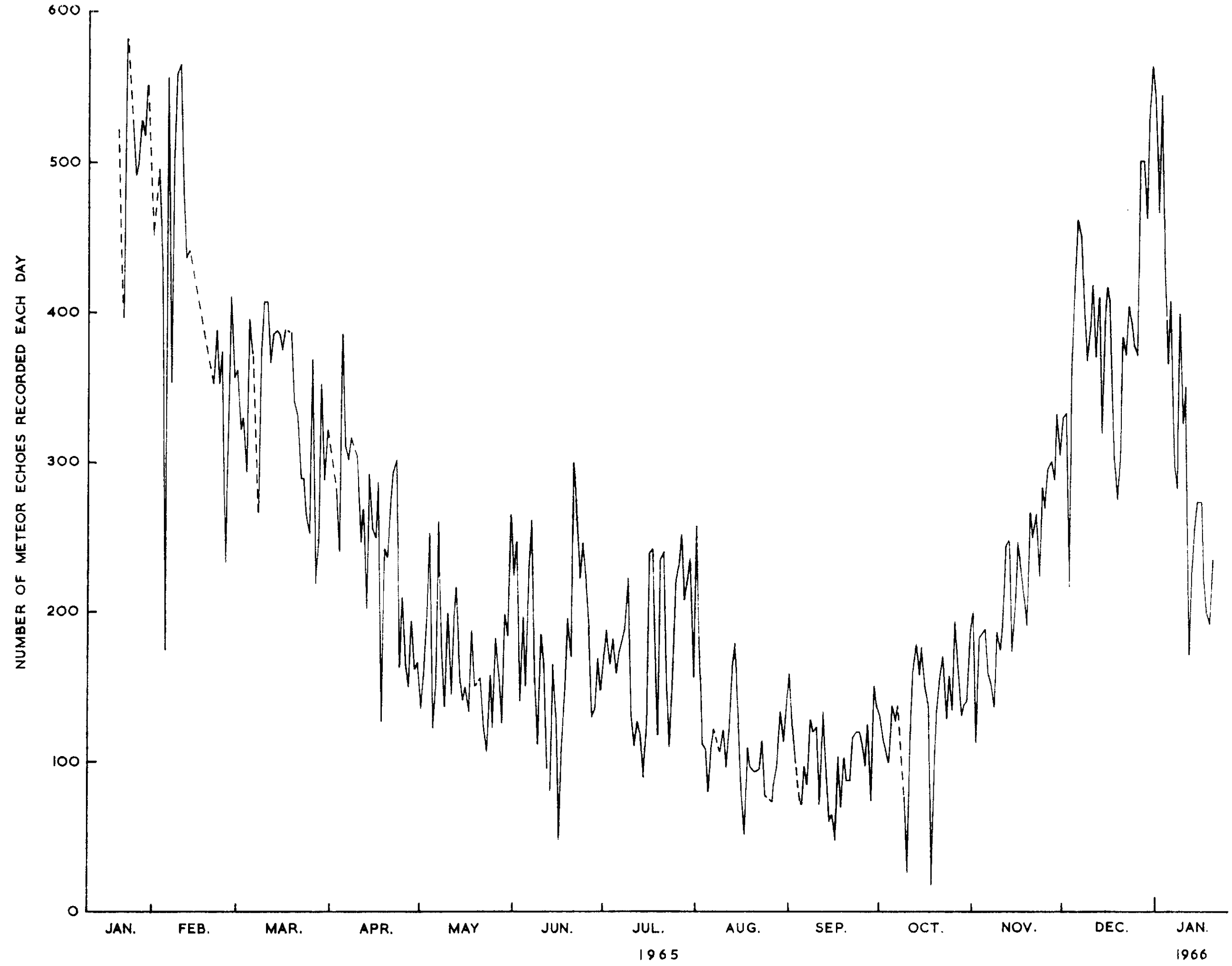


FIGURE 52
The annual variation in meteor rate.

The total meteor counts for each day are presented in Fig. 52. These totals were also derived from the tabulated meteor counts and were corrected for loss of observing time. Where less than 12 hr. were satisfactorily observed, the day has been omitted from the graph and dashed lines link the results on days adjacent to any period omitted. The δ-Aquarid shower in late July is not a prominent feature in this figure but the summer peak in activity is very pronounced.

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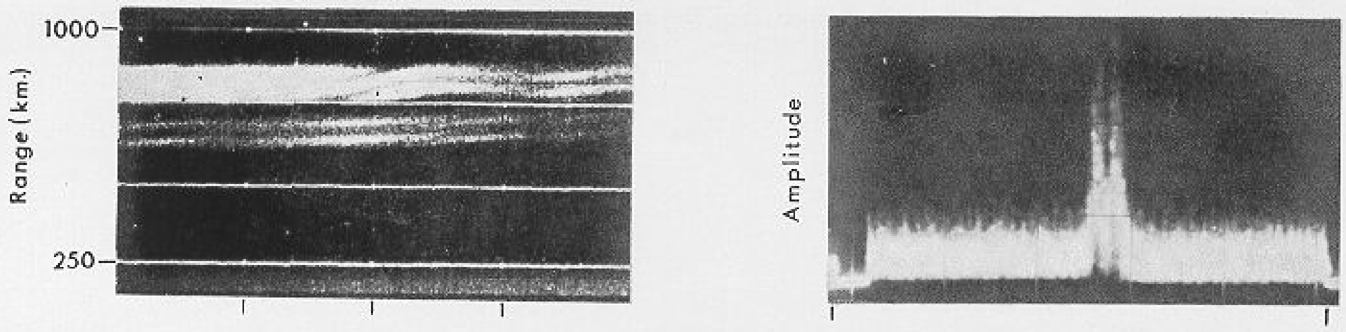
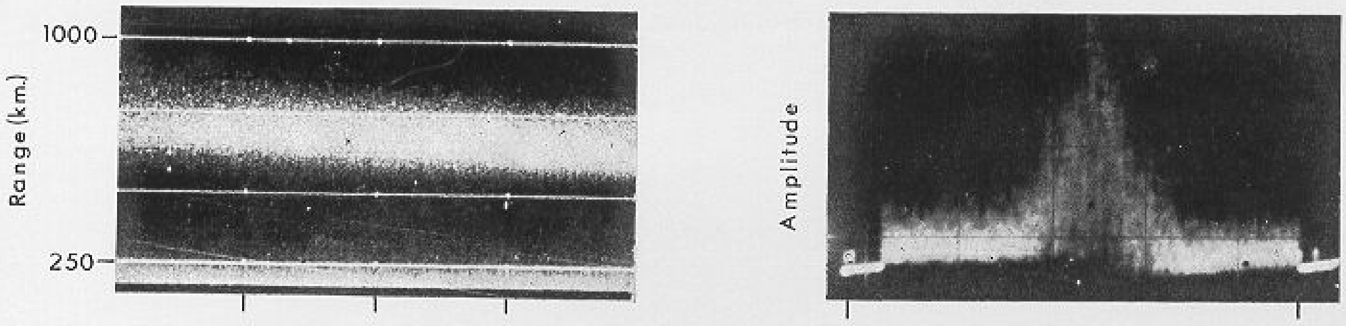
PLATE I

Examples of the radio-auroral echoes. The amplitude and intensity records were not obtained simultaneously.

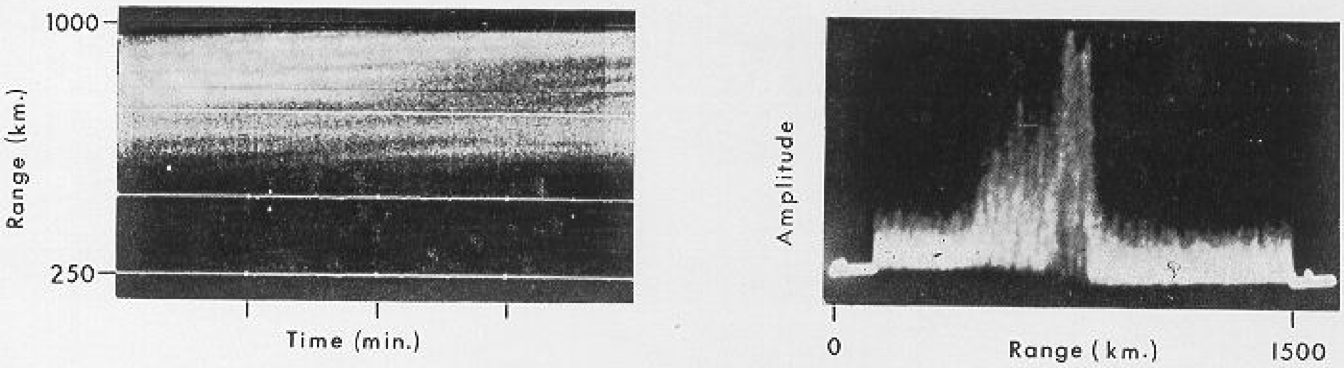
PLATE I



a. Discrete



b. Diffuse



c. Structured diffuse

Intensity range — time display

Range — amplitude display (monitor)