A STUDY OF WHISTLING ATMOSPHERICS

I. OCCURRENCE

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Summary

The occurrence of whistling atmospherics at four Australian stations (Brisbane, Adelaide, Hobart, and Macquarie Island) over the I.G.Y. period is discussed. A strong seasonal variation is observed at each station, with the maximum occurrence during local winter, and also a strong diurnal variation with a minimum during daylight hours. Whistlers are observed more commonly at about geomagnetic latitude 45°. Autocorrelation analysis suggests recurrence tendencies in the occurrence figures and cross-correlation with sunspot numbers and Adelaide data indicates an association between the two. There is little evidence of association between whistler occurrence and magnetic planetary index.

I. INTRODUCTION

The existence of occasional audio-frequency interference, in the form of descending whistles, on single-wire telephone circuits has been reported by various observers from time to time. Eckersley (1935) suggested that the energy of these " whistlers " or " whistling atmospherics " was derived from an impulsive electrical discharge, such as a lightning flash, and that the observed frequency-time characteristic was due to the propagation of this energy as very-low-frequency electromagnetic waves in a dispersive medium. A frequency-time relationship of the form $t=Df^{-\frac{1}{2}}$ (where the zero of time is taken as the time of the initiating discharge) was predicted theoretically. D, the " dispersion ", is a constant, dependent on the path parameters, for a given whistler. This relationship is still regarded as being approximately valid for the " middle " range of whistler frequencies but requires modification at " high " and " low " frequencies.

Storey (1953) postulated that the propagation paths closely follow magnetic field lines and that reflections may, on occasions, occur at the Earth end of such a line. The simplest case, and the one giving the smallest value of dispersion and hence a " short " whistler, is a generating lightning discharge in one hemisphere and an observer in the other, while a double traverse of the path with source and observer in the same hemisphere gives rise to a whistler of twice the dispersion—a " long whistler ". If several reflections occur, alternately at opposite ends of the path, then an observer in the source hemisphere observes a " whistler train " with successive dispersions in the ratios of 2 : 4 : 6 : 8, etc.

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while an observer in the opposite hemisphere observes a whistler train with dispersions in the ratios 1 : 3 : 5 : 7, etc. Whistler trains are not uncommon at some stations, and Morgan and Allcock (1956), observing at two points which were approximately geomagnetically conjugate, reported the occurrence of whistlers in a train, alternately at the two stations, with time separations and dispersions appropriate to this theory.

An occasional correlation between a nearby lightning flash and the arrival of a long whistler a short time after has been reported by Morgan (1958). Helliwell, Jean, and Taylor (1958) have observed that atmospherics which are accompanied by whistlers have, on occasions, a particular type of wave-form with a large Fourier component around 5 kc/s.

This paper is concerned with an analysis of the occurrence figures for whistlers heard at Brisbane (geographic, lat. 27° 32′ S., long. 152° 55′E . ; geomagnetic, lat. 35° 8′ S., long. 226° 9′), Adelaide (34° 57′ S., 138° 23′ E. ; 44° 9′ S., 212° 5′), Hobart (42° 52′ S., 147° 20′ E. ; 51° 7′ S., 224° 6′), and Macquarie Island (54° 30′ S., 158° 57′ E. ; 61° 1′ S., 243° 1′).

II. Experimental Details

(*a*) *Recording*

Whistlers are easily observed using a short vertical aerial, or a loop aerial, and an audio-amplifier of sufficient gain. This equipment, together with a magnetic tape recorder and timing device, constituted the basic recording apparatus (Fig. 1 (*a*)). A preamplifier was located at the base of the aerial pole and the signal fed, via coaxial cable, to the upper-track recording amplifier. Seconds pips, derived from a local oscillator triggered by the local timing device (pendulum clock, crystal clock, or chronometer), were recorded on the lower track of the $\frac{1}{4}$ in. wide magnetic tape. Recordings were made automatically from 35 to 37 minutes past each hour Universal Time (hereafter referred to as a schedule) in accordance with I.G.Y. recommendations. The local clock was compared each day with standard radio time signals.

At Brisbane, Adelaide, and Hobart a square loop aerial consisting of 12 turns of 5 m side with one corner 10 m above the ground was used. A preamplifier (Fig. 1 (*b*)) of voltage amplification 18×10^3 (±3 dB, 400 c/s to 15 kc/s) was used with filtering to minimize power mains interference and interference from V.L.F. and broadcast radio stations. Above 15 kc/s the recorder output decreased, partly because of the notch filter at 16·6 kc/s (V.L.F. station) and partly because of the fall in tape response, but a useful output was obtained to 20 kc/s. The double diode limiter (set at 1·5 V) served to clip atmospherics with a field strength of greater than about 4 mV/m. The preamplifier was calibrated by feeding a small signal in series with the loop from a very low impedance generator. Tape-recording amplifiers were of a standard pattern.

The equipment used at Macquarie Island in 1957 and early 1958 (until February 24) used a 10 m vertical aerial and a similar preamplifier to that used above but of somewhat lower gain. This equipment is estimated to have had an overall gain of one-half to one-third of those used at the other stations. It is hereafter referred to as the B-recorder. After February 24, 1958, equipment kindly lent by Dr. R. A. Helliwell of Stanford University was used. This equipment (hereafter referred to as the A-recorder) is described in ASTIA Document No. AD 110184 (Stanford University).

(*b*) *Playback and Analysis*

Tapes were played back through an amplifier of standard design. The time of occurrence (to the nearest second) of whistlers was noted as well as an aural estimate of strength on a 1–5 scale. The ear appears to be the most sensitive detector of whistlers, but the weakest whistler which can be heard varies from observer to observer and also depends on the frequency range and the dispersion of the whistler as well as the diffuseness (see Part II (Crouchley and Finn 1961)). Weak whistlers of limited frequency range, high dispersion, and large diffuseness

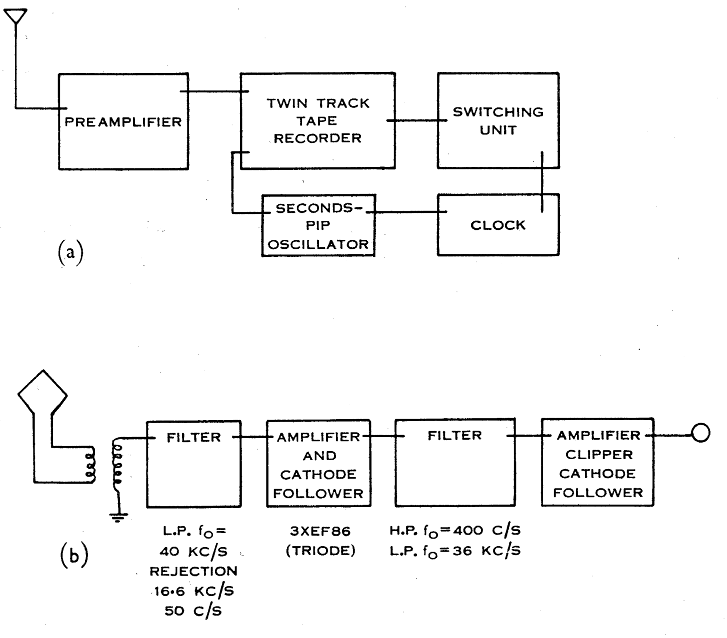

Fig. 1.—Apparatus for recording whistlers.

are difficult to detect. In practice the level of observability is usually determined by the amount of noise due to high harmonics of the power mains frequency and naturally occurring noise from lightning discharges. It was not, in general, possible to distinguish between long and short whistlers by ear, owing to the large number of crash type atmospherics recorded and also to the variation in frequency range of whistlers. Without a clear-cut initiating atmospheric it is easy to confuse a short whistler, of extended frequency range, with a long whistler of more limited frequency range, but lasting about the same time. It is estimated that a signal of electric field strength about 15 μV/m would be the limit of detectability in the absence of external noise.

The output from the replay-amplifier was also fed to 18 tuned circuits the outputs of which were displayed on 1 in. cathode-ray tubes arranged along a straight line. The deflections of the spots of the cathode-ray tubes were photographed on slowly moving film. In this way it was possible to measure the dispersions of about one-quarter of the whistlers which could be heard. The information concerning relative abundances of short and long whistlers was obtained from these films.

III. Variations in the Number of Whistlers Observed

(a) *Seasonal Variation*

The four Australian stations showed a maximum whistler activity from a few weeks before the winter solstice (southern hemisphere) to a few weeks after the spring equinox, in contrast to two northern hemisphere stations of similar longitude (Toyokawa, geographic 34° 50′ N., 137° 22′ E.; geomagnetic 24° 30′ N., 203° 30′; Wakkanai, 45° 22′ N., 141° 41′ E.; 35° 20′ N., 206° 0′) for which data have been published (Fig. 2). These two stations showed a maximum of activity between winter solstice (northern hemisphere) and spring equinox. The size of this peak is clearly less in 1958 than in 1957 for Brisbane and Hobart, almost certainly so for Macquarie Island (A-recorder more sensitive than B-recorder) but the absence of recordings in July and August 1957 makes a comparison uncertain for Adelaide. Likewise the two northern hemisphere stations showed a decrease in 1958 as compared with 1957, for the period of peak activity in the southern hemisphere.

A lesser peak is apparent between summer solstice and autumnal equinox at Brisbane and Adelaide, while at Hobart it assumes an importance comparable with that of the winter peak. Macquarie Island shows no comparable increase in activity at the beginning of 1958, but December 1958 and January 1959 were months of high activity and thus this station may also have, on the average, a similar seasonal variation.

No seasonal variation in the occurrence of long whistlers was apparent at Brisbane, but only a small number was recorded. At Adelaide and Hobart long whistlers were more common in summer and at the end of winter than during the winter peak of activity. During the winter peak the number of short whistlers increased and the number of long whistlers decreased thus causing the ratio of the number of long whistlers to the number of short whistlers to fall by a factor of about four times.

(b) *Variation of the Number of Whistlers Observed with Geomagnetic Latitude*

As is suggested by the graphs of Section III (*a*), whistlers occur much more frequently at stations at middle geomagnetic latitudes than at the lower or higher latitude stations. This point is illustrated by Figure 3, which is a plot (full lines, dots) of the average number of whistlers per schedule (over a year) against geomagnetic latitude. For all the stations, except Adelaide, the averaging period was from the beginning of July 1957 to the end of June 1958. In the case of Adelaide the period selected was from October 1957 to September 1958, as records were not available for July and August 1957. If the 1958 months of peak occurrence were less active in 1958 than in 1957 at Adelaide, as at the other

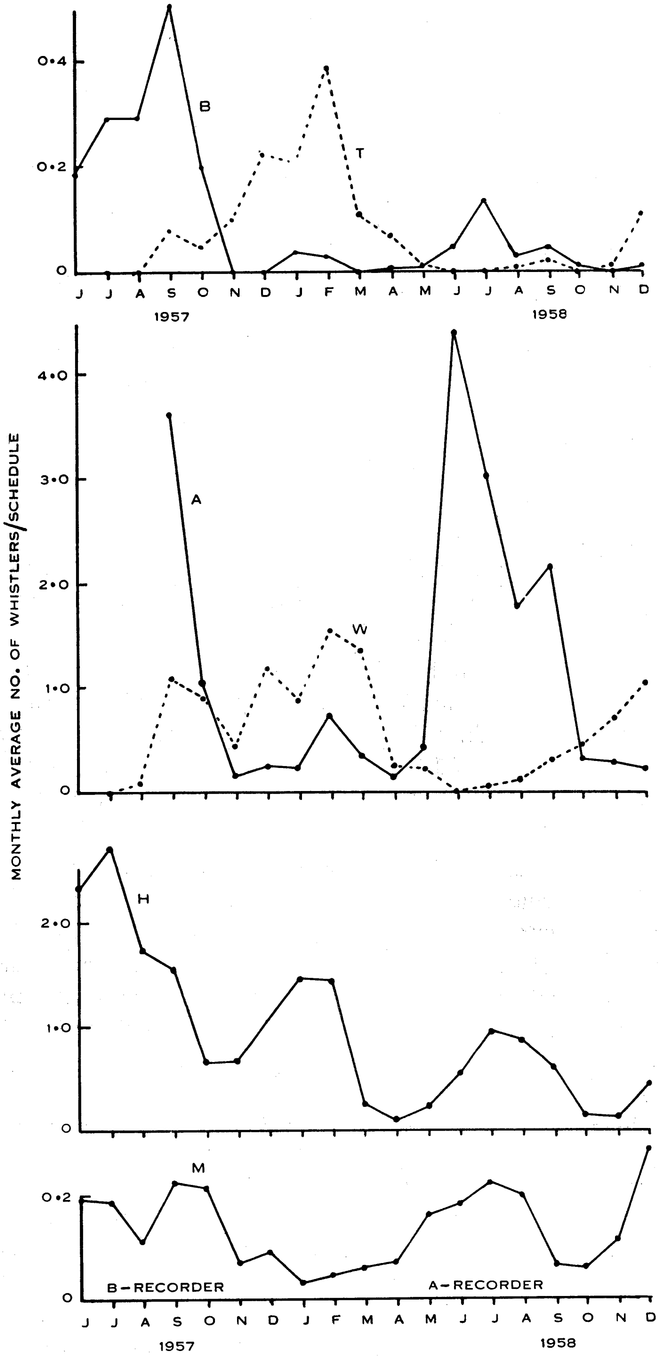

Fig. 2.—Seasonal variation of whistler occurrence. A, Adelaide; B, Brisbane; H, Hobart; M, Macquarie Island; T, Toyokawa; W, Wakkanai.

stations, then the value plotted for this station is somewhat low in comparison to the values plotted for the other stations. Included in the diagram are also values for the two Japanese stations, Toyokawa and Wakkanai (July 1957 to June 1958), for Godhavn (Ungstrup 1959) and the zero value reported by Koster and Storey (1955) for geomagnetic latitude 10°.

The discrepancy between the Brisbane and Wakkanai values is reduced by plotting against magnetic (dip) latitude rather than geomagnetic latitude (dashed line, crosses). However, subsequent work makes it appear likely that the reported values for Brisbane were unduly lowered by man-made interference.

The percentages of strong whistlers (i.e. strengths greater than 2) for the year were 3·2, 4·8, and 5·8% respectively for Brisbane, Adelaide, and Hobart. The means of the corresponding monthly percentages were 2·5, 4·0, and 6·3%,

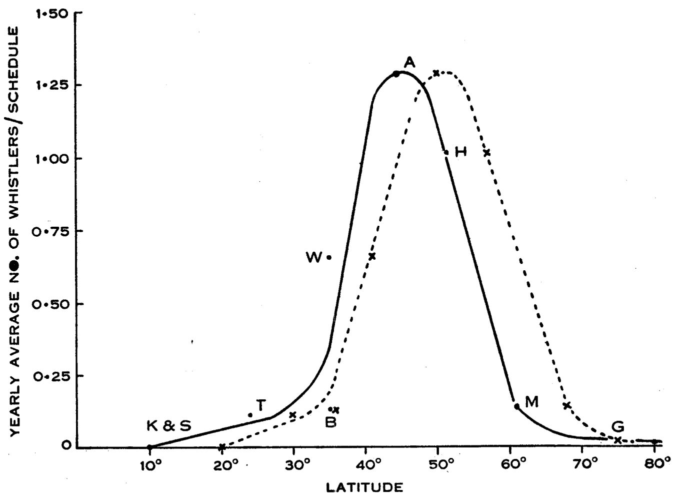

Fig. 3.—Variation in whistler occurrence with latitude. ●—— Geomagnetic; × --- Magnetic; G, Godhavn; K & S, Koster and Storey; other abbreviations as in Figure 2.

and the difference between the Hobart and Brisbane mean values was 2·3 times their combined standard error. The differences between the other pairs of means were in each case less than twice the appropriate standard error; thus only the Brisbane-Hobart difference may be considered significant at the 5% level.

The percentages of long whistlers were as follows: Brisbane 4%, Adelaide 12%, Hobart 36%, and Macquarie Island 40%, although the two extreme values are of lower significance than the two middle ones, due to the smallness of the samples from these two stations. Similar percentages for Toyokawa and Wakkanai are 1 and 2% respectively. The proportion of long whistlers thus seems to increase as the latitude increases and not to have a maximum at the same latitude as the maximum of whistler occurrence.

(c) *Diurnal Variation*

The average number of whistlers per schedule (over one year, as for latitude variation) against local mean time of recording is plotted in Figure 4 (*a*), and Figure 4 (*b*) shows a similar plot for the data, divided into three groups for months around the time of maximum activity, the summer submaximum, and the intermediate months. These three groups have been designated " winter-peak " (June, July, August, September), " summer-peak " (January, February, March), and " intermediate-months " (October, November, December, April, May).

Each station shows a minimum of whistler occurrence during daylight hours, and, for the winter peak, a decrease in the width of the minimum with increase in latitude. This minimum is also wider in summer than in winter. The incidence of whistlers increases to a maximum value during the evening or night hours.

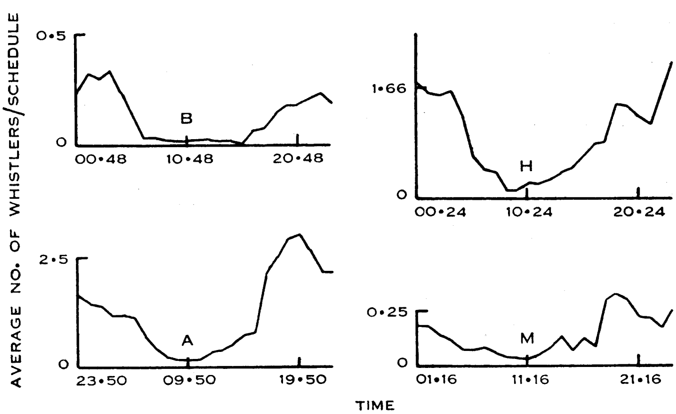

Fig. 4 (*a*).—Diurnal variation of whistler occurrence (yearly average).

At Brisbane this maximum occurs around 0200, at Adelaide around 1900, while at Hobart activity is high from late afternoon to about midnight for the winter months and is maximum two or three hours after midnight for the summer peak. Macquarie Island, which is less consistent than the other stations in behaviour from month to month, shows, on the average, a maximum of activity in the late afternoon.

At Adelaide long whistlers were very seldom observed during the day-time, although some of the short whistlers were observed during daylight hours. During the night the ratio of long to short whistlers varied somewhat erratically from schedule to schedule. At Hobart long whistlers were absent during the morning but they appeared about midday, and the ratio of long to short whistlers was somewhat higher during the night than in the afternoon, although, as for Adelaide, it varied somewhat erratically from schedule to schedule.

(d) *Day-to-Day Variation*

The total number of whistlers observed in a day (taken from midday to midday, Eastern Standard Time, in order not to assign one evening to two separate days) varied from zero up to, on a few occasions, 10 or 15 times the yearly-average for a day. Figure 5 shows a sample plot over one month for September 1959 at Brisbane.

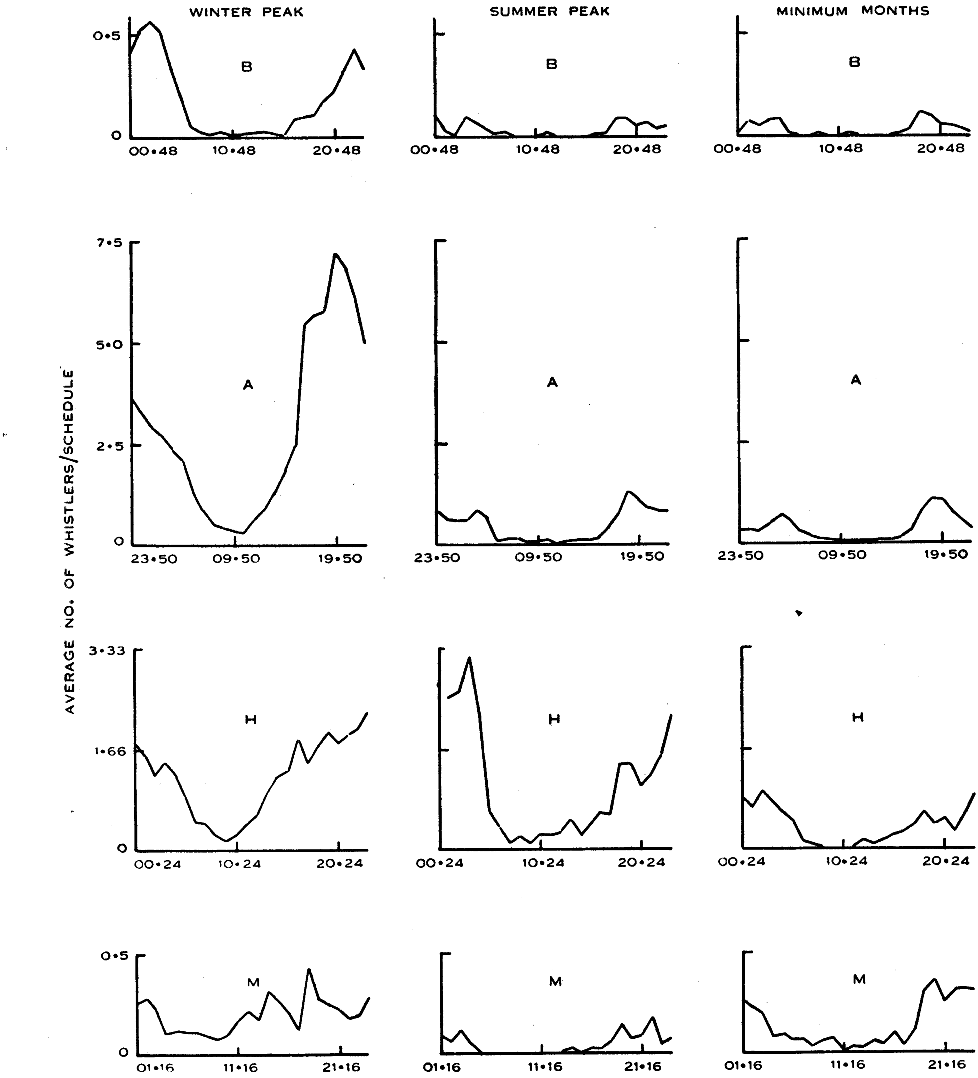

Fig. 4 (*b*).—Diurnal variation for groups of months.

IV. Correlation Analysis of Daily Total Whistler Occurrences

Approximately five months of records about the winter peak of activity in 1958 were selected for a correlation analysis. This subgroup was taken to give a reasonable size of sample and also to minimize any effect of seasonal variation.

(*a*) *Autocorrelation Analysis*

Autocorrelation coefficients for lags up to 65 days were calculated on daily totals for Brisbane, Adelaide, Hobart, and Macquarie Island and also on Adelaide day-whistlers, Adelaide night-whistlers, Adelaide weak-whistlers (strengths 1

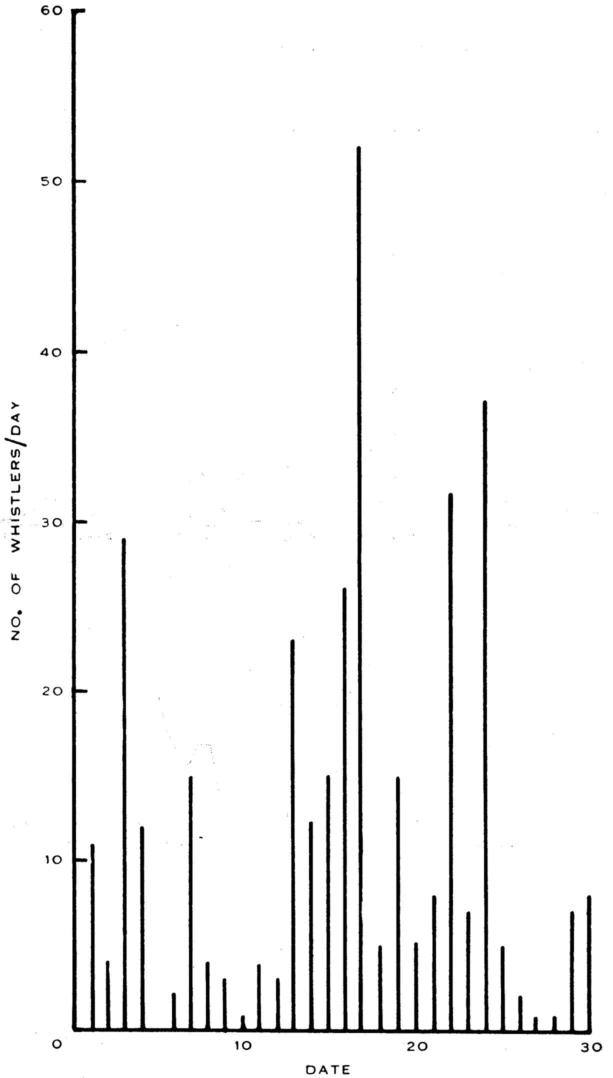

Fig. 5.—Day-to-day variation in whistler occurrence. (Brisbane, September 1957.)

and 2), Adelaide strong-whistlers (strengths 3, 4, and 5), Hobart daily totals, and Hobart night-whistlers (as week-end day-time recordings were not made at this station), and Macquarie Island daily totals. Figure 6 is a plot of the correlation coefficient against the number of days' lag for Brisbane daily totals, Adelaide day-time values, Adelaide night-time values, Hobart daily totals, and Macquarie Island daily totals.

Both Brisbane daily totals (which because of the diurnal variation essentially represent night-time values) and Adelaide day-time values show evidence of a 17-day recurrence tendency with, for Brisbane, a possible period of about half this value. The Adelaide night-time values show a marked positive region from 26 to 29 days and this is repeated again from 55 to 58 days suggesting a recurrence

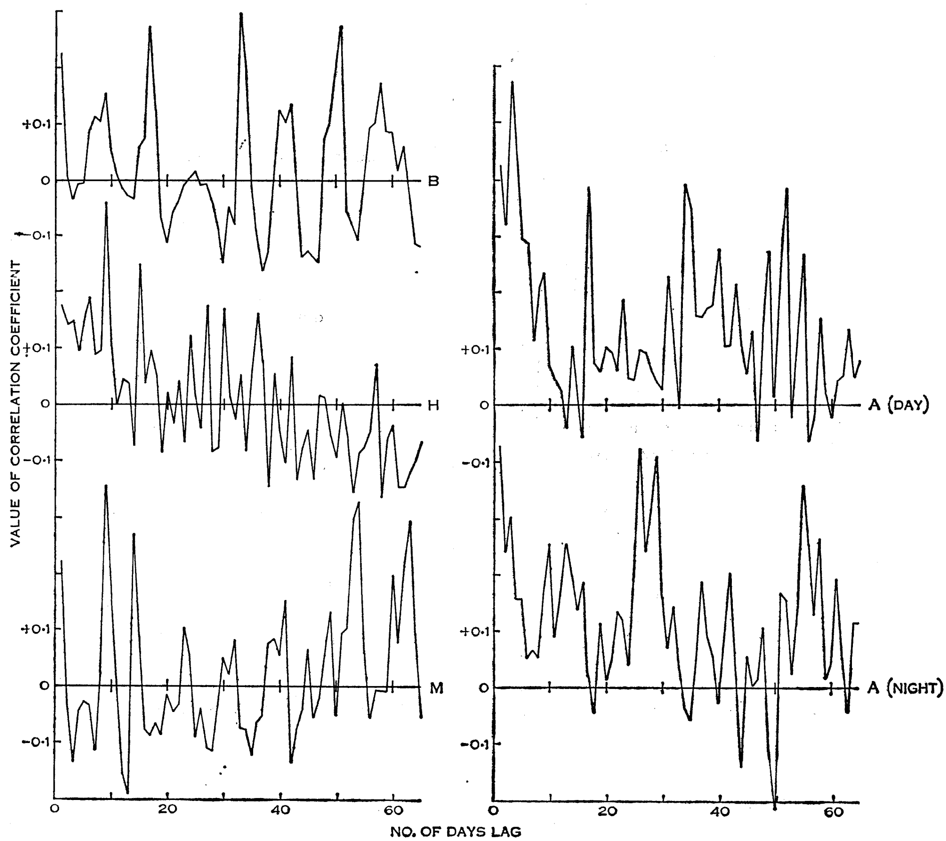

Fig. 6.—Autocorrelograms of daily totals.

period of about 27–28 days. This pattern is also apparent, but to a lesser extent, in the correlogram of Adelaide total values, Adelaide weak-whistlers, and Adelaide strong-whistlers. Hobart exhibits positive peaks at 9 days and 15 days, but these are not repeated at multiples of these values and a considerable degree of randomness is apparent over the rest of the plot. Macquarie Island shows clear-cut positive peaks at 9, 15, 54, and 63 days while several of the lesser peaks show a separation of 9 or 15 days.

Serial correlation is apparent for the first 5 days in Adelaide suggesting that at this station whistlers tend to occur or be absent for a few days at a time, but for the other stations there is little association, even over 2 days.

While it is difficult to assess the significance of individual values of the correlation coefficient in these circumstances, because of the number of coefficients calculated and of the serial correlation present in the data, the number of values used in the individual calculations (varying from 115 to 50 for Macquarie Island and 150 to 70 for the other stations) was such that the larger values would have been considered significant at the 1% confidence level if treated as isolated values.

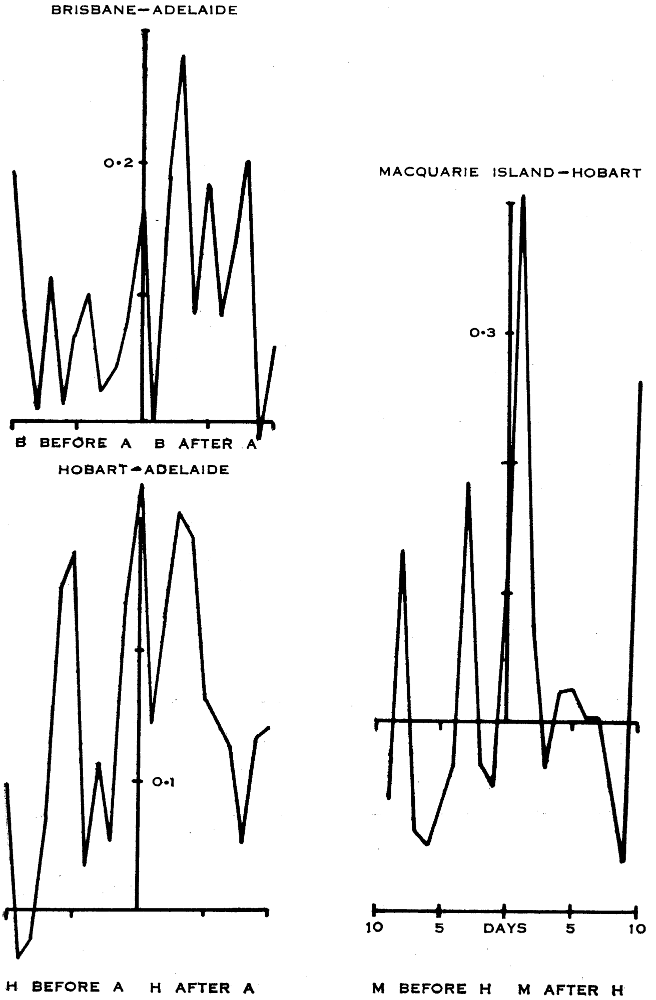

Fig. 7.—Cross-correlograms between stations.

(b) *Inter-station Correlation*

Figure 7 shows lag cross-correlograms with delays of up to plus and minus 10 days between the nearest pairs of stations. There are indications of activity (or lack of activity) in Adelaide being followed by a similar occurrence rate in Brisbane 2 or 3 days later, of Adelaide and Hobart occurrence rates moving in a

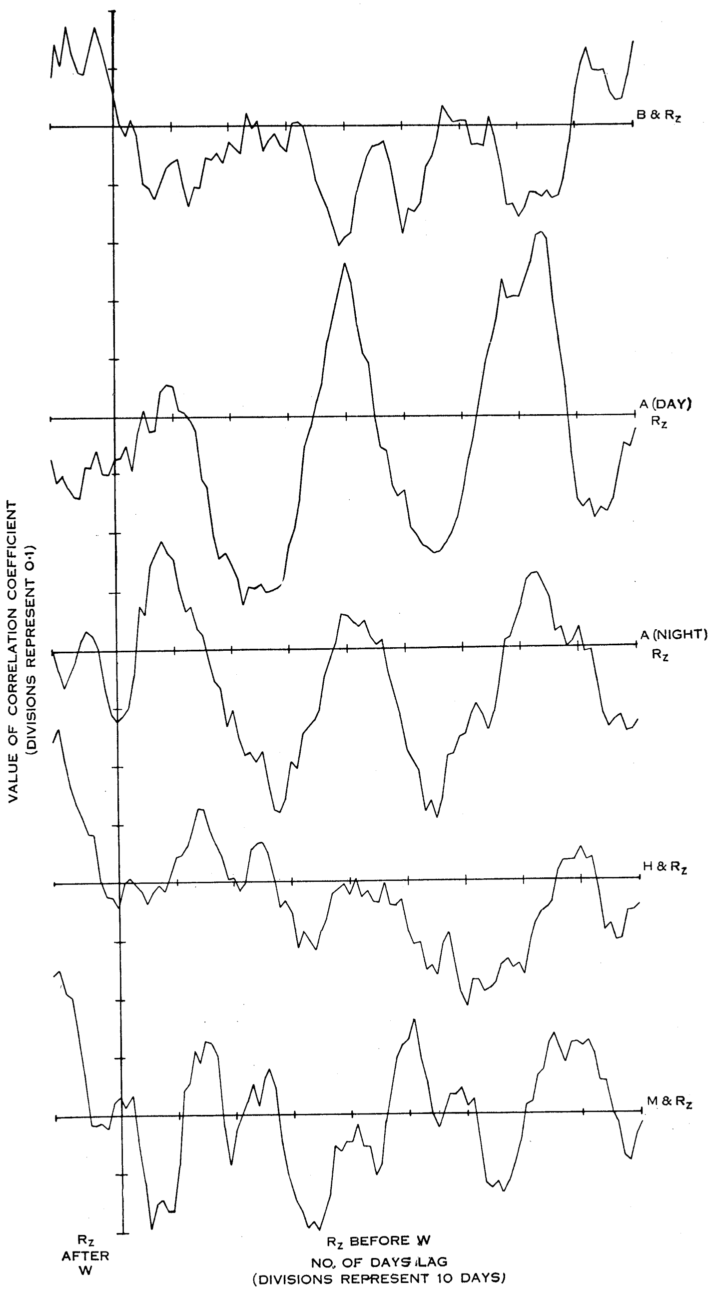

Fig. 8.—Cross-correlograms between whistler daily totals and sunspot number (R_z).

similar fashion on the same day and also of Hobart exhibiting a similar change to Adelaide 3 days after Adelaide. The largest value of correlation coefficient is observed between Hobart values and Macquarie Island values 1 day later and the effect of the 9-day recurrence tendency in the values from these stations, as demonstrated by the autocorrelograms, is apparent in the cross-correlograms.

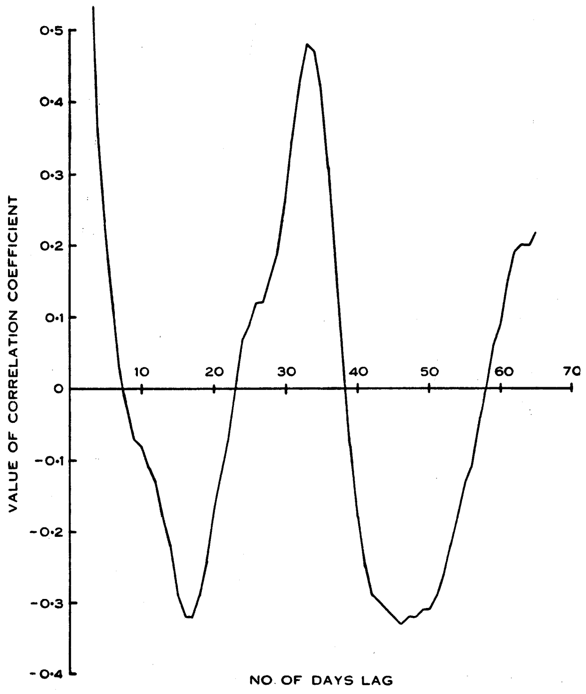

Fig. 9.—Autocorrelogram of R_z.

V. Cross-correlation between Whistler Daily Totals and Sunspot Number

The daily total values, as used for the calculation of the autocorrelograms of Section IV (*a*) were used for the calculations of correlation coefficients with Zurich Provisional Relative Sunspot Numbers (R_z) from R_z 90 days before whistler daily totals to R_z 10 days lagging on the whistler data. The cross-correlograms are shown in Figure 8, while Figure 9 shows the autocorrelograms of R_z over approximately the same period. The cross-correlogram for the Adelaide day-time values and, to a lesser extent, that for the Adelaide night-time values are similar to the autocorrelogram of R_z and suggest a possible association between whistler occurrences at this station and sunspot number. A time difference of the order of 10 days (or 10 plus a multiple of approximately 30 days) is apparent between the two variables. There is little indication of any association between whistler activity and sunspot number at the other stations.

VI. Association between Whistler Occurrence and Magnetic K-index

The lag cross-correlograms between daily whistlers totals and the daily magnetic K-index sum (SK_p) have been calculated from SK_p 60 days before to 60 days after the whistler data (Fig. 10). For zero lag Brisbane shows a significant

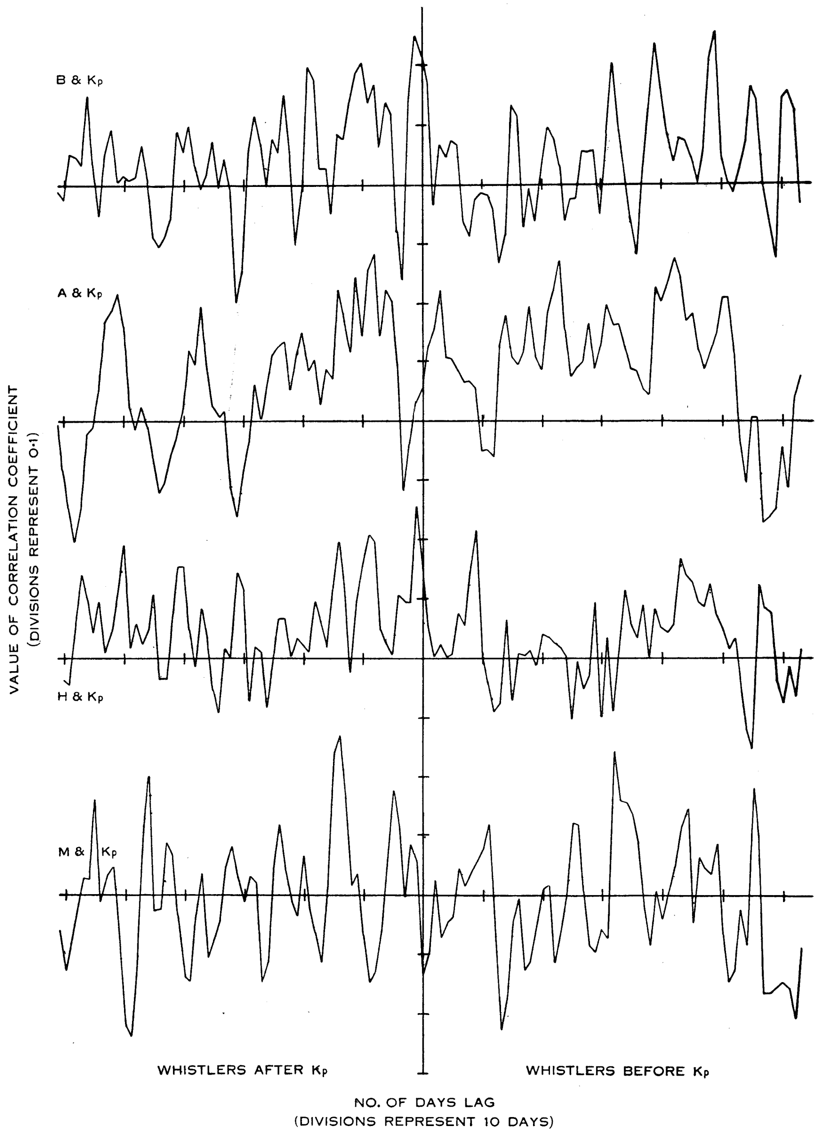

Fig. 10.—Cross-correlograms between whistler daily totals and daily sums of K_p.

positive correlation, Adelaide a small positive correlation, Hobart a somewhat larger positive correlation, and Macquarie Island a negative correlation. Larger values of correlation coefficient are observed with other delays but there is no systematic behaviour either between stations or for any one station. Thus there is no well-defined association between whistler occurrence and the magnetic K-index daily sums. Similar lag cross-correlograms were calculated using the K-values for Toolangi (the nearest magnetic observatory to Adelaide and Hobart) and the K-values for Macquarie Island. These cross-correlograms were very similar to those reproduced.

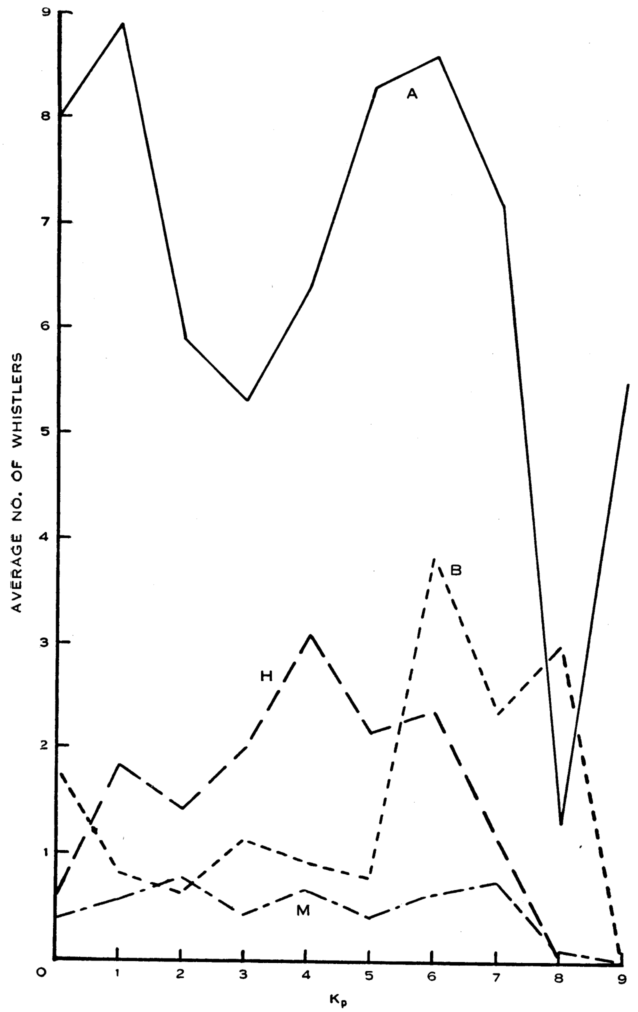

Fig. 11.—Association between K_p and average number of whistlers for each value of K_p.

A plot of the average number of whistlers observed in a 3-hr period (as used for determining the values of K_p) against the value of K_p for approximately 5 months of data is shown in Figure 11. There is a suggestion that whistlers occur more frequently for low values of K_p at high latitudes and for high values of K_p at low latitudes, but the large whistler occurrence for low value of K_p

reported for Adelaide and the relative infrequency of high values of K_p make the result inconclusive. Such a result would be in agreement with the values of correlation coefficient for zero lag reported above.

VII. Discussion

The number of whistlers observed at any station must depend on several factors, namely, the number of suitably-placed sources, the absorption in the lower ionosphere at both ends of the path, and the conditions along the path in the upper ionosphere. As individual whistlers can often be heard at stations separated by distances of the order of 1000 km and studies of diffuseness (Part II of this series) (Crouchley and Finn 1961) suggest that the actual whistler channel has a smaller cross-sectional dimension than this, then propagation conditions between the ionosphere and ground (wave-guide type propagation) or over the surface of the Earth may also be of importance.

No detailed information of thunderstorm activity is available for the conjugate points of the Australian recording stations. Even if this were available the problem is complicated by the general lack of continuous detailed correlation between lightning flashes and whistlers. Kimpara (1955) has published maps showing the distribution of sources of atmospherics in the region of the conjugate points of the Australian stations for September 1953, February 1954, and March 1954. The overall impression conveyed by these maps is that lightning is more common around the conjugate point of Brisbane than around those of Adelaide and Hobart and (as in most other locations) it is more common during the day than the night. The same author (1959) has also given values of a "thunderstorm index" for 1000 km around Wakkanai (which is of the order of 1200 km from the Adelaide conjugate point). This index shows large values for summer months (northern hemisphere) and small values for winter months. Australian meteorologists (Bath, personal communication 1959) observe a general maximum of thunderstorms in summer with submaximum late in winter. The seasonal variations of whistlers reported are thus in general agreement with the meteorological data, the large peak in whistler occurrence being due to summer thunderstorms in the opposite hemisphere producing short whistlers and the lesser peak being in part due to local summer storms in the observer's hemisphere, giving long whistlers.

The diurnal variation in whistler activity is, however, apparently at variance with the meteorological data, and one must postulate, as has been done by other workers (Helliwell and Morgan 1959), that absorption in the lower ionosphere is a significant factor in reducing the number of whistlers observed during daylight hours. If this were the only effect involved, one might expect the daylight part of the curve to be symmetrical about midday, whereas the observations indicate higher afternoon than morning values. It seems likely that this is due to the usual rise in lightning activity after midday.

The peak of whistler occurrence around geomagnetic latitude 45° is a somewhat surprising result, as is the rapid decrease in occurrence towards the equator, for the path length decreases for lower latitudes and thunderstorm activity increases. A decrease in occurrence at high latitudes is to be expected on account of the scarcity of sources and the extreme length and height of the path. While absorption in the lower ionosphere and interference from atmospherics increase at lower latitudes, it seems unlikely that these factors are adequate to explain the observed decrease. Accordingly, it is suggested that propagation conditions along the higher parts of the path are more favourable at mid latitudes than at low latitudes. The relatively large number of echoes and trains observed at middle to higher latitudes and the scarcity of even two-hop whistlers at low latitudes also substantiate this suggestion. The increase in the proportion of long whistlers at Hobart compared to Adelaide together with the decrease in thunderstorm activity with increasing latitude suggests that the most favourable conditions for whistler propagation may be at a somewhat higher latitude than that indicated by the overall occurrence figures. A line of force passing through the slot between the two Van Allen radiation belts cuts the Earth about this region. The recent work of Smith, Helliwell, and Yabroff (1960) on the guiding of whistlers by ducts explains the relative scarcity of whistlers at low latitudes in terms of the relatively large enhancements of ionization required to produce effective guiding along paths commencing at low latitudes.

The day-to-day variations in observed occurrence rates are almost certainly due in large measure to variations in source activity. However, for Adelaide there is some evidence of an association with sunspot number, particularly during daylight hours. The delay between sunspot number and whistler occurrence makes it unlikely that the effect is one of absorption. In view of the correlation between whistler dispersion and sunspot number with a lag of between one and two months reported by Allcock and Morgan (1958) it seems more likely that the reported effects are due to changes in the main body of the path rather than at the ends.

The other periodicities suggested by the autocorrelograms may be due to the same periodicity of whistler source activity or to a recurrence of favourable propagation conditions. Thus, for example, if solar disturbance produced regions of enhanced electron density on day and night sides of the Earth in the upper Van Allen radiation belt and if these regions rotated from west to east relative to the Earth with a period of 18 days but decayed appreciably in this time, then one would expect the 9-day peaks as observed in the Hobart and Macquarie Island records. The peak in the Hobart-Macquarie Island cross-correlogram for Macquarie Island data one day after Hobart data and the difference in longitude (Macquarie Island approximately 20° E. geomagnetic of Hobart) is consistent with this suggestion. Likewise, Brisbane and Adelaide-day autocorrelograms suggest a 17-day occurrence tendency. Such rotations have been suggested by Gold (1959) but with periods of the order of minutes or hours. A similar analysis of local atmospherics and of whistler data from other stations might assist the interpretation.

VIII. Conclusion

It seems likely that the observed variations in frequency of whistler occurrence are predominantly due to variations in the frequency of occurrence of suitable lightning flashes, but there are indications that changes in propagation conditions along the path have a significant influence. A systematic study of " whistler-mode " propagation from a suitably placed, powerful V.L.F. station, i.e. a known source, would enable the latter variations to be studied separately.

The difference between variations in whistler activity and " chorus " activity (Crouchley and Brice 1960) recorded at Australian stations confirms the view that these are separate and distinct phenomena.

IX. Acknowledgments

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