SOME EFFECTS OF NUCLEAR EXPLOSIONS ON THE IONOSPHERE

By G. G. Bowman*

[*Manuscript received May* 30, 1962]

Summary

Examination of spread-F conditions at Brisbane and other stations adjacent to the Pacific area, together with an investigation of $h'F_2$ and f_0F_2 changes at the time, suggest that three disturbances propagated from the site of the nuclear explosion at Johnston I. on August 1, 1958. Somewhat similar variations of ionospheric parameters occurred after the explosion on the same site on August 12, 1958. The average speeds of these disturbances were 1666, 647, and 333 m/s.

It is suggested that the first is probably a hydromagnetic disturbance, and that pressure waves travelling in sound channels at 80 and 180 km respectively may be responsible for the other two disturbances.

Ionospheric conditions at Brisbane following Russian nuclear explosions in October 1961 tend to support the findings from the Johnston I. explosions.

I. Introduction

During August 1958 two nuclear explosions occurred in a region of the Pacific Ocean close to Johnston I. ($16\cdot7°$ N., $169\cdot4°$ W.). The first occurred at 1050 U.T. on August 1 at a height of 60 km, and the second at 1030 U.T. on August 12 at a height of 30 km.

During this period a rotating-loop direction-finding system was operating at Brisbane, recording pulsed echoes at $3\cdot84$ Mc/s, reflected from the ionosphere, and originating from a transmitter on the same site. The rotating-loop system consisted of two loops 2 m square spaced 10 m apart, with their planes parallel to each other and perpendicular to the booms joining them. The echo strengths received at the two loops were compared in a difference unit, the output recording a null when the system was orientated perpendicular to the direction-of-arrival of the echo. Plate 2, Figure 1, is a typical sample of the records obtained, representing a plot of virtual range against time. The system rotated concontinuously and had a period of rotation of 2 min. The gain of the receiver was changed by 45 dB every $2\cdot5$ sec. This gave information about the relative echo strengths of the main trace and the satellite traces, and was effective in producing better resolution for satellite traces. Further details of the system are given by Bowman (1960*a*).

Characteristics of the spread-F echoes recorded by the direction-finding system some hours after the first explosion are examined in the present paper for a possible association with the event. An analysis is also made of the varia-

* Physics Department, University of Queensland, Brisbane.

tion of ionospheric parameters (at these times) from ionograms taken at Brisbane and other stations adjacent to the Pacific area. Ionograms for Brisbane after the Russian nuclear tests in October 1961 are also examined.

II. Spread-F and Travelling Disturbances

Cummack and King (1959) and Matsushita (1959) have already reported F_2-layer disturbances following these mid-Pacific nuclear explosions in August 1958.

Spread-F echoes recorded at Brisbane on two separate occasions in the hours immediately following the first explosion may possibly be associated with the explosion. On each occasion the onset of spread-F was accompanied by a sharp fall in the critical frequency of the F_2 layer (f_0F_2) and a sudden height rise of the F_2 layer. These variations are discussed in later sections of this paper. The rotating-loop record and ionograms for the first onset are shown in Plate 1, Figures 1 and 2. Plate 1, Figure 3, shows the Brisbane ionograms for the second spread-F onset.

A previous analysis (Bowman 1960*a*) has indicated that, on most occasions, at Brisbane, spread-F results from off-vertical reflections from a ripple structure in the contours of equal ionization density of the F_2 layer, the wavelength of these ripples varying from 20 km to over 100 km.

The spread-F reported here is indistinguishable from that recorded on other occasions. Plate 2, Figure 1, shows the fine structure of the satellite traces and in addition, the direction-of-arrival of this frontal phenomenon is clearly defined. The direction-of-arrival measured relative to true north is 050° or 230°, as the rotating-loop system produced a 180-degree ambiguity in results for most of the period of operation.

During the two months of recording by the rotating-loop system in July and August 1958, directions-of-arrival of about 050° (or 230°) are rare, and an analysis of results (Bowman 1960*a*) shows that the probability of recording these directions is about 1 in 50. Since 050° is the direction of the explosion site from Brisbane, an association with the explosion seems probable.

The local time (Brisbane) of the first explosion was 2050 and the first spreading commenced at 2318. This indicates a speed of propagation from the explosion site (6400 km distant) of 723 m/s. These spread-F echoes lasted for 2 hours, during which time the direction-of-arrival was consistently 050°. Until the arrival of the second disturbed period at 0214 (local time) no further spreading occurred. However, high-multiple traces were recorded during this period. These are indicative of an extremely shallow ripple structure (Baird 1956), and the direction-of-arrival of these signals (north-west) suggested that the F_2 layer had resumed its normal night-time condition. Spread-F echoes from ripple structures come predominantly from the north-west (Bowman 1960*a*). With the onset of the second disturbed period the direction-of-arrival of the spread-F echoes was again 050°. These also lasted for 2 hours. Again, if the second disturbance travelled out from the explosion site, a speed of 314 m/s is indicated.

If one imagines a ripple structure in the F_2-layer ionization density contours at the time of these disturbances, spreading out from the explosion site, it is

NUCLEAR EXPLOSION EFFECTS ON THE IONOSPHERE

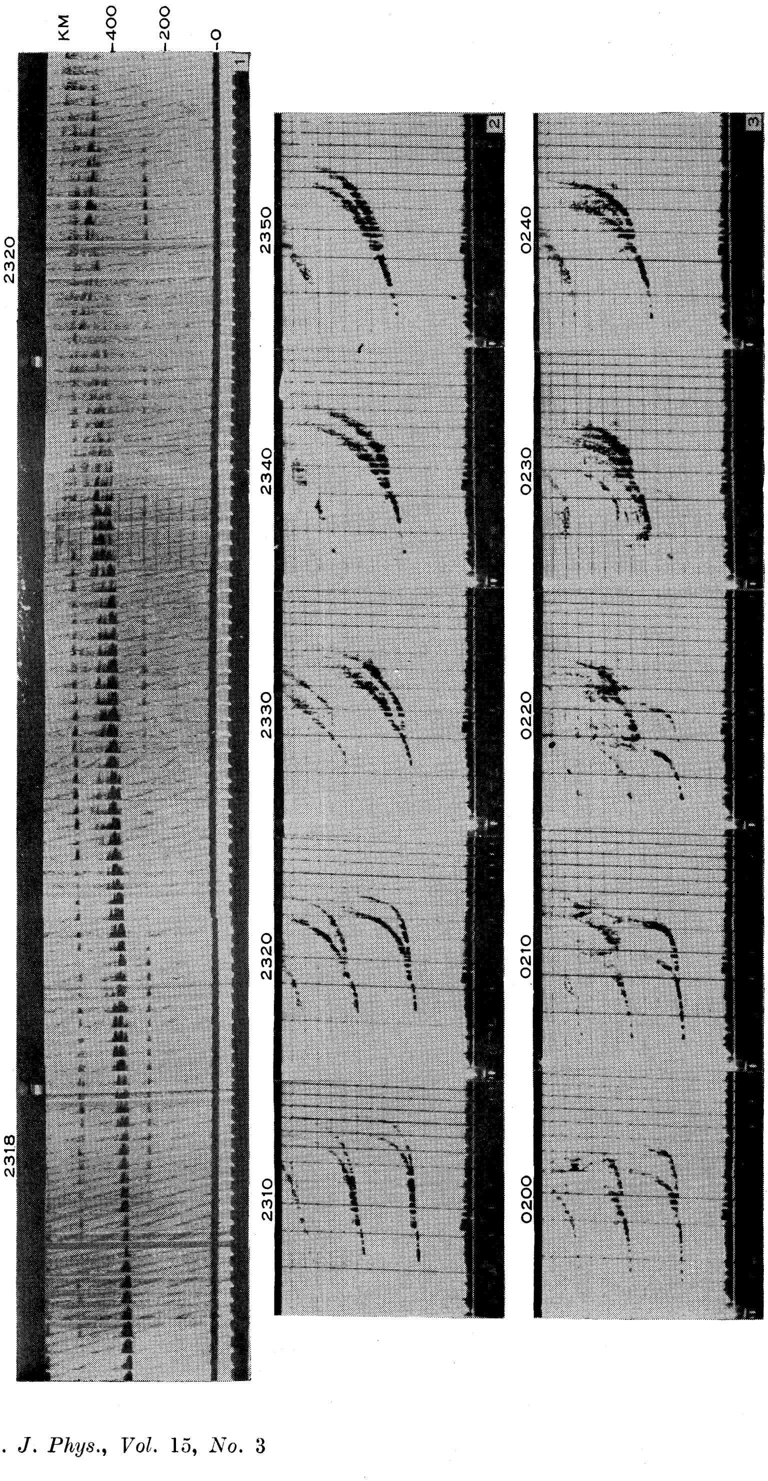

Fig. 1.—Rotating-loop h'/t record (3·84 Mc/s) at the time of commencement of the first spread-F disturbance on 1.viii.58.
Fig. 2.—Ionograms for Brisbane indicating start of first F_2-layer disturbance following explosion on 1.viii.58.
Fig. 3.—Ionograms for Brisbane indicating start of second F_2-layer disturbance following explosion of 1.viii.58.

NUCLEAR EXPLOSION EFFECTS ON THE IONOSPHERE

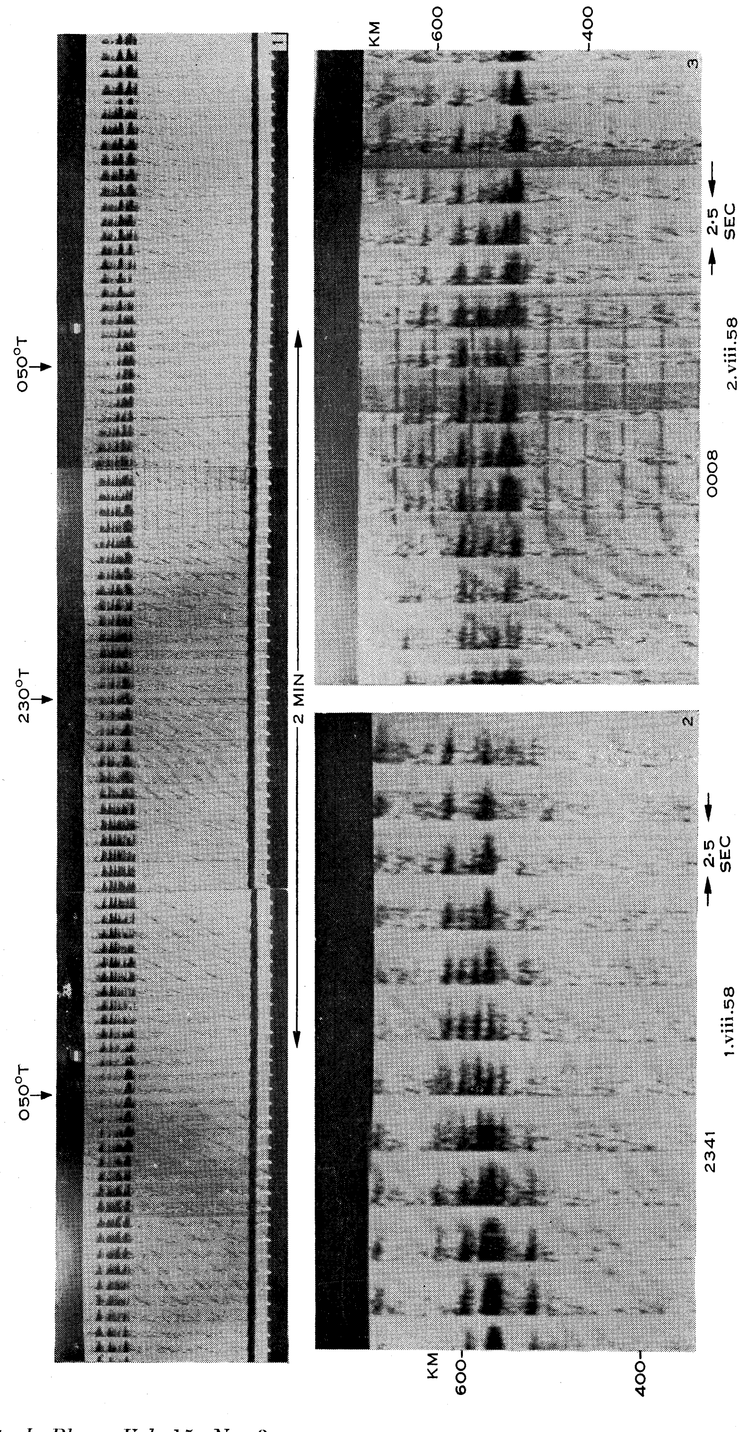

Fig. 1.—Rotating-loop $h't$ record (3·84 Mc/s) at about 2350, 1.viii.58 indicating nature of spread-F satellite traces of the first disturbance and the direction-of-arrival of satellite traces.

Fig. 2.—Rotating-loop record at 2341 on 1.viii.58 showing discreteness of satellite traces.

Fig. 3.—Rotating-loop record at 0008 on 2.viii.58 showing traces from an approaching ripple and a receding ripple occurring simultaneously.

evident that two fine-structure patterns will be produced by the fast swept-gain unit; one pattern from reflections from ripples moving away and another from the approaching ripple structure. However, on occasions when the normal fading of the satellite echoes is favourable, a complete set of traces (approximately evenly spaced) from one azimuth only can be recognized. Plate 2, Figure 2, shows such an occasion when five satellite traces, from a receding wave structure, can be recognized. The true height of the layer (for plasma frequency 3·22 Mc/s) can be calculated (Schmerling 1958) and, if it is assumed (as an approximation) that the satellite traces experience the same retardation as the echo for normal incidence, true ranges for each trace can be estimated. These in turn allow a

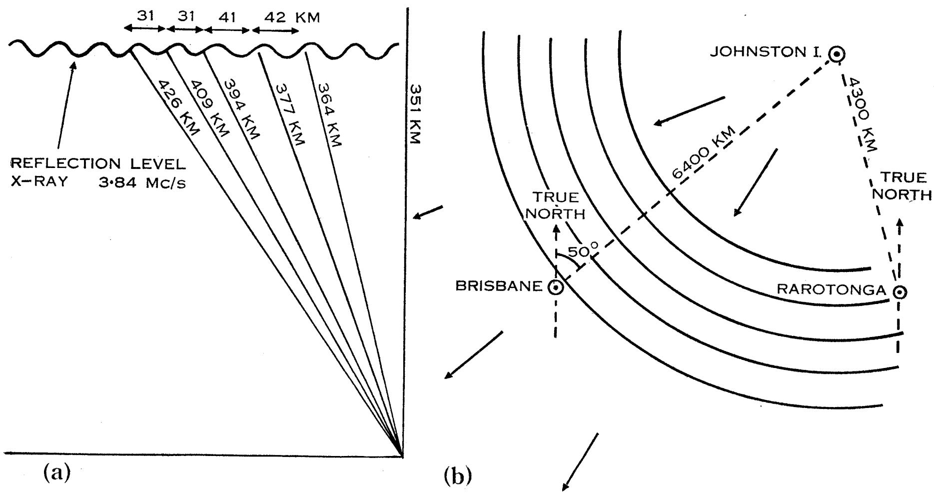

Fig 1.—(*a*) Diagram of cross section of proposed ripple structure in ionization density contours calculated from rotating-loop record.
(*b*) Plan view of proposed ripple structure of disturbance.

calculation of the wavelength spacings of the ripples. Figure 1 shows, for this occasion, wavelengths ranging around an average value of 36 km. The calculated speed of 723 m/s gives a period of oscillation (or time of transit of one wavelength) of 0·8 min.

During the spread-F periods being considered, occasionally, when the normal fading was not severe, the identity of traces from receding or approaching ripples can be retained for a certain length of time. This is normally not possible because of the number of spread-F traces present at the one time. Plate 2, Figure 3, shows an occasion when a receding trace and an approaching trace can be identified at the same time, and followed for an appreciable fraction of a minute (25 sec for the approaching trace and $27\frac{1}{2}$ sec for the receding trace). Figure 2 is a tracing of this record. Care was taken to choose a period when the f_0F_2 and the $h'F_2$ values remained constant, so that the recorded change in range represents a real change in the range to the irregularity. True ranges to the base of the layer and to the irregularities were calculated as before, and from the rate of change of range, the speed of approach, or the speed of recession, was calculated (McNicol, Webster, and Bowman 1956).

These calculations gave a value of 639 m/s for the approaching trace, and 833 m/s for the receding trace. The average value of 736 m/s is comparable with the speed of 723 m/s calculated from the onset time of spread-F at Brisbane.

The rotating-loop system was also operating at the time of the second explosion but it did not register any spread-F echoes. This was also true of the ionograms at Brisbane at the same time.

The spread-F experienced at Rarotonga (4300 km from Johnston I.) after the first explosion has been illustrated by Cummack and King (1959). From the ionograms they have published the speed of propagation for the first disturbance, calculated from the onset time of the first spread-F echoes, is 785 m/s. At 0230 local time (U.T. −11 hr) the nature of the disturbance changes. Although the traces remain spread, a series of cusps form on the o-ray and x-ray traces. These gradually move down and eventually form the main trace. The speed of propagation calculated from the onset time of this second disturbance is 347 m/s.

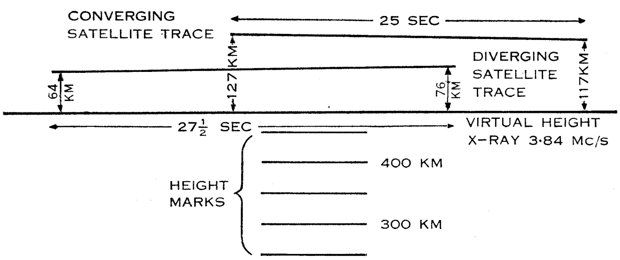

Fig. 2.—Tracing of essential features of Plate 2, Figure 3.

Matsushita (1959) has published ionograms for Maui, only 1450 km from the explosion site, which show disturbances related to the second explosion. Although the type of disturbance cannot strictly be referred to as spread-F, satellite traces do exist in the form of cusps similar to those reported for Rarotonga. These traces are reminiscent of the large-scale day-time travelling disturbances reported by Munro and Heisler (1956) and Heisler (1958). The first cusp appears at 1104 U.T. giving a speed of propagation of 708 m/s. A second cusp-like disturbance becomes evident at 1150 U.T. giving a speed of propagation of 306 m/s.

It will be noticed that the onset times of the F_2-layer disturbances, for all three stations considered in this section, indicate that at least two disturbances are propagated, the speed calculations for each disturbance being reasonably consistent for each station. At Brisbane the second spread-F does not start until the first has disappeared, but at Rarotonga and Maui, because of their proximity to the explosion site, the disturbance effects overlap.

III. Variations in f_0F_2

Changes in the f_0F_2 values at Brisbane, Rarotonga, and Maui at these times of interest suggested an investigation of the f_0F_2 variation at a number of stations adjacent to the Pacific area.

In Figure 3 the variation of f_0F_2 for 24 hours around the time of the explosion is shown for 9 stations for one or other of the two explosions. Also shown is the diurnal variation of the average value for the months of July and August in the case of the first explosion (1.viii.58) and the average value for August in the case of the second explosion (12.viii.58). For each case the difference (Δf_0F_2) between the average value and the observed value is plotted.

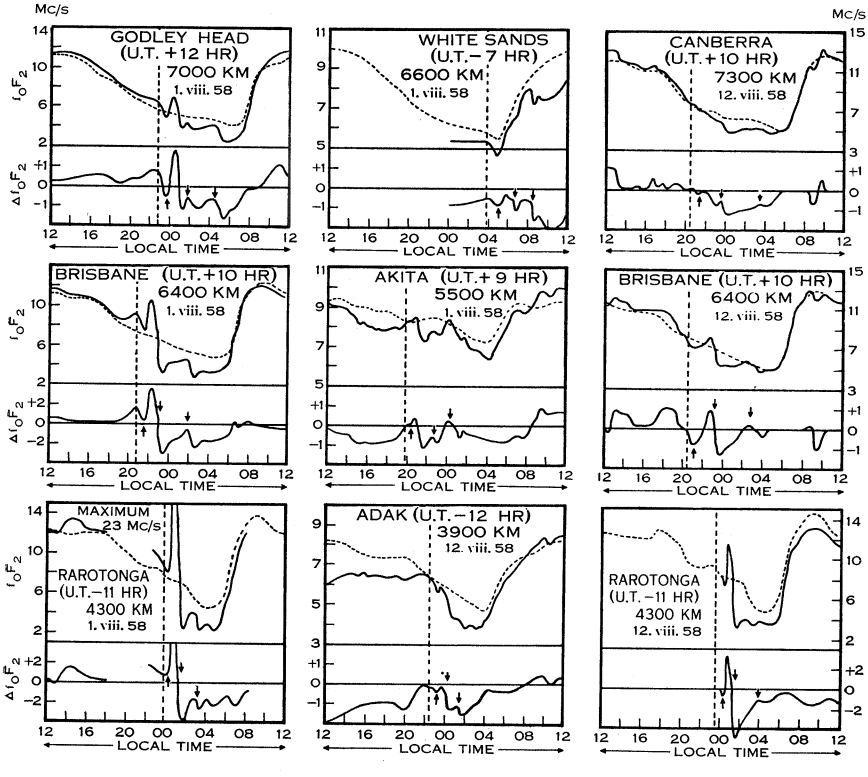

Fig. 3.—Variation of f_0F_2 around the time of nuclear explosions on 1.viii.58 or 12.viii.58 for nine stations. Each variation compared with an average value ; for July and August for the explosion on 1.viii.58, and for August only for the explosion on 12.viii.58. Variations from average values plotted as Δf_0F_2 curves in each case.

In all cases an increase in Δf_0F_2 occurs at times of up to an hour or more after the explosion time. This increase is followed sometime later by two decreases in the value Δf_0F_2 similar to the decreases which occurred at Brisbane for the first event.

The time interval between the explosion time and the occurrence of the decreases is plotted in Figure 4 against station distance from the explosion site for the stations used in Figure 3, and also for other stations in the area (Fig. 5). The points group themselves into approximately two straight lines, suggesting that at least two disturbances propagate from the explosion site. The line slopes suggest speeds of 647 and 333 m/s respectively. The positions on Figure 4 related to phenomena at Novaya Zemlya (Russia) will be explained in Section V.

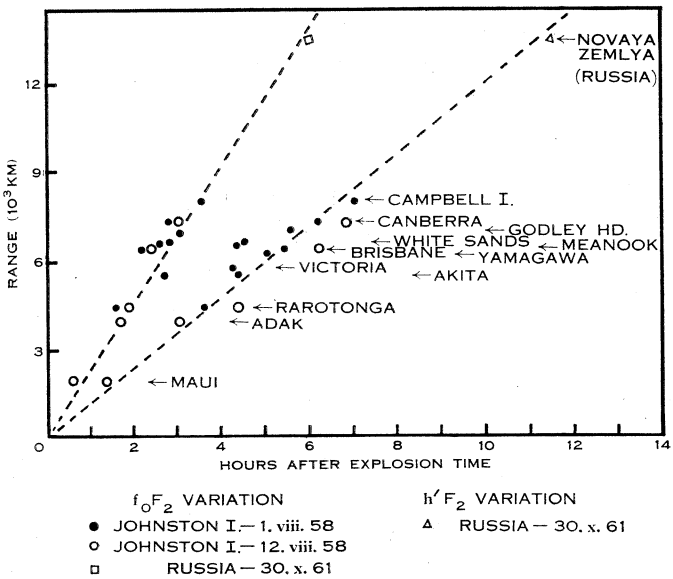

Fig. 4.—Plot of time interval from explosion time to sudden drop in Δf_0F_2 value for various stations adjacent to the Pacific area, against range of station from explosion site (Johnston I.). The Δf_0F_2 drop and $h'F_2$ oscillation at Brisbane following Russian explosion on 30.x.61 also indicated.

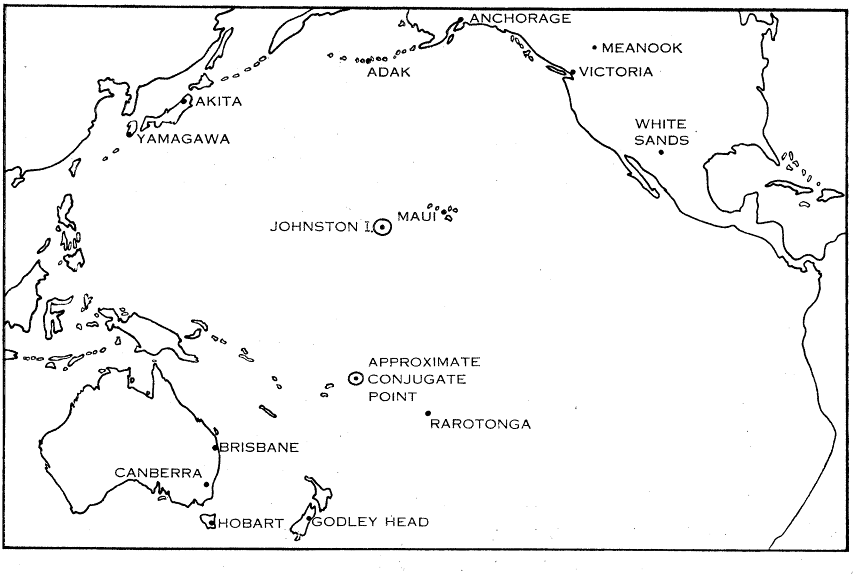

Fig. 5.—Map of Pacific area showing the location of various stations used in this analysis.

Variations in f_0F_2 due to other causes will tend to mask the explosion effects. In order to partially eliminate these unwanted variations, an attempt has been made to average the Δf_0F_2 variation for some hours after the explosions. Each Δf_0F_2 curve of Figure 3 (except Rarotonga on 1.viii.58) has been taken and

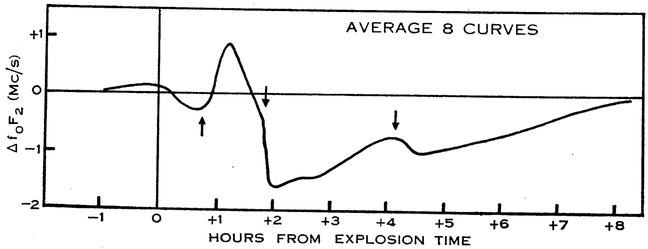

Fig. 6.—Average variation of eight Δf_0F_2 curves, normalized to represent the variation for each curve for an imaginary station 5000 km from the explosion site.

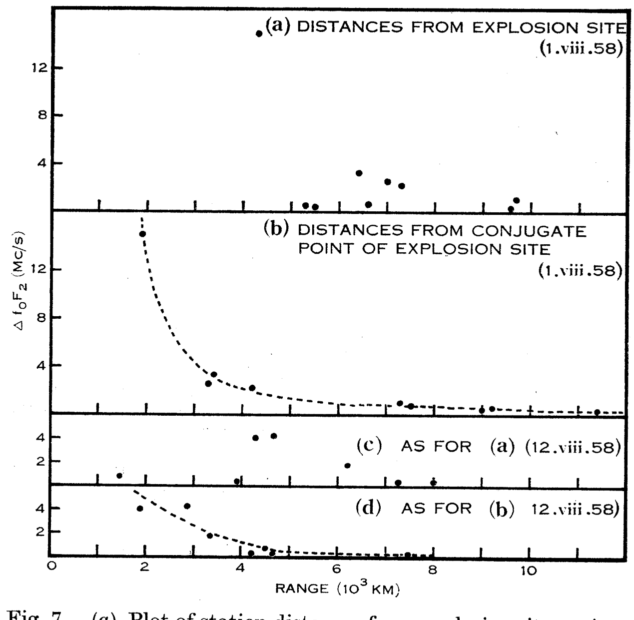

Fig. 7.—(*a*) Plot of station distances from explosion site against recorded Δf_0F_2 increases after explosion on 1.viii.58.

(*b*) Same as (*a*) except that distances from conjugate point of explosion site.

(*c*) Same as (*a*) except that points are for explosion on 12.viii.58.

(*d*) Same as (*b*) except that points are for explosion on 12.viii.58.

changed to produce a Δf_0F_2 curve which might have been produced had the station concerned been situated 5000 km from the explosion site. The original curves were modified by taking the time of each variation (increase or decrease in Δf_0F_2 value) and calculating a new time for the normalized curve. This was calculated on the assumption that the time of occurrence of any variation is proportional to the distance of the station from the explosion site. An average was then taken of the variations of these eight normalized curves, and the result is shown by Figure 6. Rarotonga (1.viii.58) was omitted from this calculation because the large Δf_0F_2 increase (15 Mc/s) after the explosion would give undue bias to the averaged curve. (All other increases are less than 4 Mc/s.)

Figure 6 shows the three effects clearly. There is a sharp increase in Δf_0F_2 three-quarters of an hour after explosion time, one decrease and slow recovery at 1 hr 50 min, followed by a similar decrease and slow recovery at 4 hr 15 min.

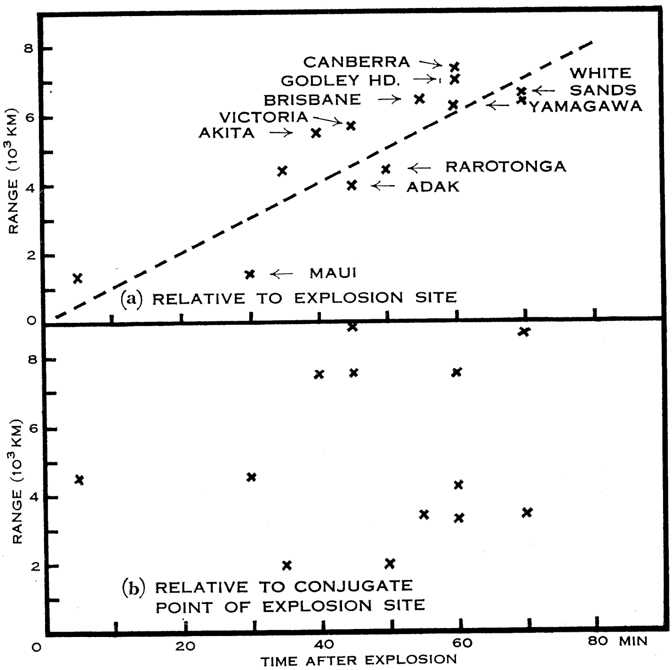

Fig. 8.—(*a*) Plot of station distances from explosion site against time interval from explosion time (1.viii.58 or 12.viii.58) to onset of Δf_0F_2 increase.
(*b*) Same as (*a*) except that distances from conjugate point of explosion site.

These times infer propagation speeds of 1861, 750, and 333 m/s. Almost full recovery has occurred 8 hours after explosion time for this imaginary station 5000 km distant from the explosion site.

The proximity of the station to the explosion site seems to be less important to the magnitude of the Δf_0F_2 increase than its proximity to the conjugate point (approximately 14·5° S., 175·5° W.) of the explosion site. Figure 7 shows the magnitude of the increase for various stations plotted separately against distances from the explosion site and distances from the conjugate point. For both explosions the distribution of points is much more ordered with the conjugate point as the reference location.

The foregoing might mean that the disturbance responsible for the increase in the Δf_0F_2 value propagates from the conjugate point. However, Figure 8 shows that, when both reference points are considered, propagation from the explosion site seems more likely. The distribution of points suggests a speed of propagation of about 1666 m/s for this phenomenon.

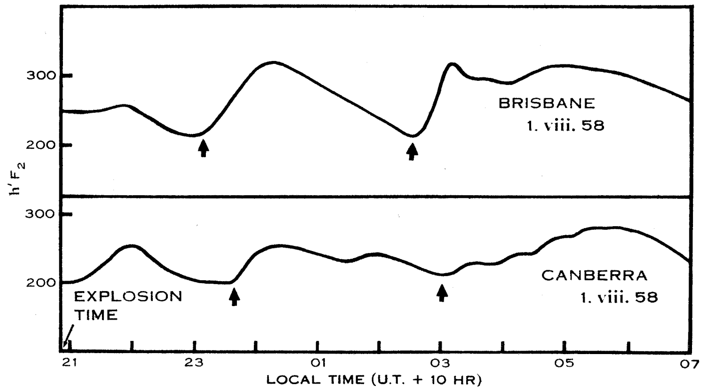

Fig. 9.—Plots of $h'F_2$ variations at Brisbane and Canberra following the explosion at Johnston I. on 1.viii.58.

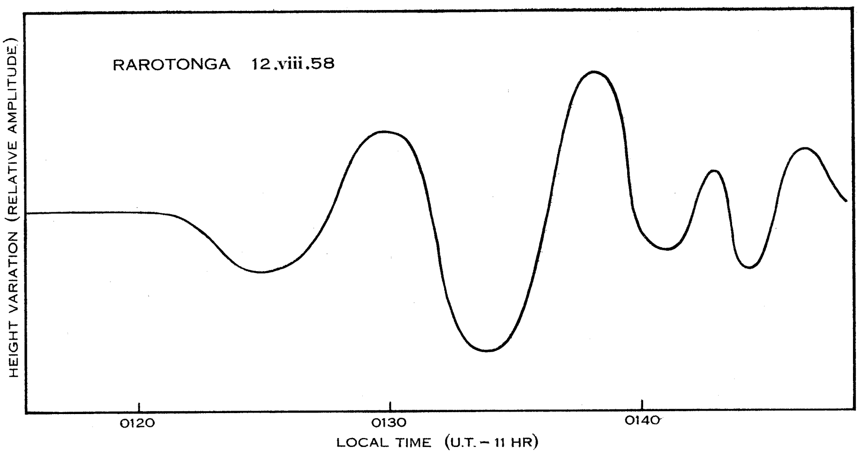

Fig. 10.—Oscillations in value of $h'F_2$ (Rarotonga, after Johnston I. explosion 12.viii.58) relative to a smoothed variation (from Fig. 3 of Cummack and King 1959).

IV. Height Variation of the F_2 Layer

Consideration has also been given to the height variations of the F_2 layer in the hours following the explosions. Figure 9 shows the $h'F_2$ variation at Brisbane following the first explosion. The two major height rises are coincident with the onset of spread-F, and the sharp fall in f_0F_2. The height rises associated with the two disturbances arriving at Canberra for the first event are also shown on Figure 9. No spread-F followed immediately after these height rises, but the second rise was followed by an oscillation in the $h'F_2$ value with a period of about

30 min. A disturbance speed of 328 m/s (calculated from the onset time) suggests a ripple structure with a wavelength of 590 km.

Cummack and King (1959) have carried out a true height analysis from the ionograms (made at 2 min intervals) for Rarotonga for the second event, when apparently no spread-F was recorded. The height increase commencing at 0123 (local time) also shows an oscillation in the value of $h'F_2$. A plot of this oscillation in the lower part of the F_2 layer, relative to a smoothed value of $h'F_2$ at the time, is shown on Figure 10. The average period of about 8 min indicates a wavelength for a possible ripple structure of 307 km for the disturbance speed of 647 m/s (calculated using the time of onset).

For both $h'F_2$ curves in Figure 9 (Brisbane and Canberra), and the height variation from the $N(h)$ analysis for Rarotonga, it is evident that the disturbance responsible for the initial increase in Δf_0F_2 also has a height rise associated with it. This is also apparent from the published ionograms for Rarotonga for the first event (Cummack and King 1959).

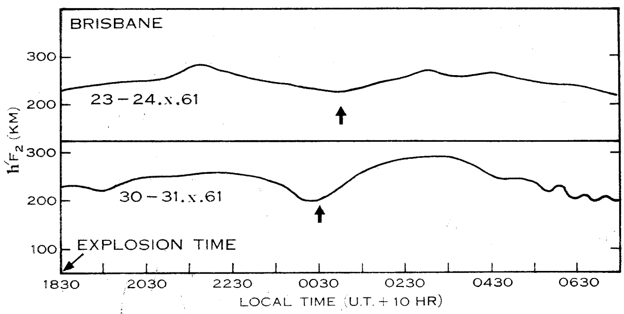

Fig. 11.—Variation of $h'F_2$ at Brisbane following Russian explosions on 23.x.61 and 30.x.61.

V. Russian Nuclear Explosions (October 1961)

When the U.S.S.R. began a series of nuclear tests in September 1961, most of the analysis described in the previous sections had been completed, so that high energy explosions detonated at this time at great heights in the atmosphere, provided a means of checking the results already obtained.

Two of the Russian tests are suitable for investigation. One explosion, reported to be of strength about 30 megatons, was detonated at some height in the region of Novaya Zemlya at about 0830 U.T. on 23.x.61. Another nuclear device (of 50 megatons or more) was exploded in a similar region at 0833·33 U.T. on 30.x.61 (Rose, Oksman, and Kataja 1961). The $h'F_2$ variations at Brisbane for a number of hours after the explosions are shown in Figure 11. Figure 12 shows Δf_0F_2 curves (for Brisbane) calculated in the same way as in Figure 3 for a 24 hr period embracing the explosion period.

There is no definite sign of a sudden increase in Δf_0F_2 after either explosion. Although there is some evidence, after the event on 23.x.61, of a fall in Δf_0F_2 and an associated height rise around midnight (local time), more convincing evidence occurs after the event on 30.x.61. At 0030 on 31.x.61 a sharp drop of Δf_0F_2 coincides with an appreciable height rise and the onset of spread-F echoes which lasts until 0420 (local time). If this disturbance did originate at the explosion site, it would have travelled at least 13,500 km in the 5 hr 57 min it took to reach Brisbane with an estimated speed of 630 m/s. Tracings of the Brisbane ionograms from 0020 until 0210 inclusive on 31.x.61 are shown on Figure 13.

A second disturbance, travelling with a speed similar to that found in the previous sections, would be expected to arrive at about 0600 (local time). No $h'F_2$ increase, Δf_0F_2 decrease, or spread-F conditions are obvious from the Brisbane ionograms. The fact that a day-light period is involved here may be of significance. However, commencing at 0530 (local time) there is an oscillation of the $h'F_2$ value with a period of about 30 min. At 0600 (local time) the commencement of microbarometric pressure oscillations (period about 8 min) was

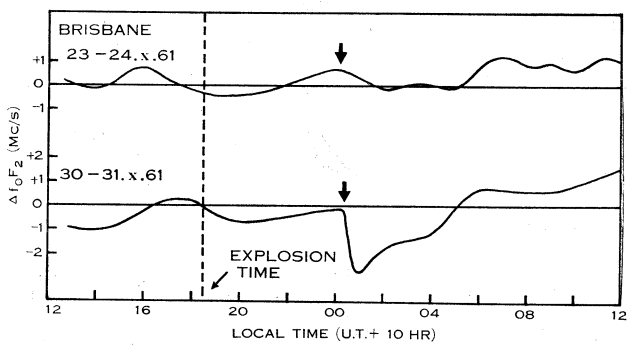

Fig. 12.—Variation of Δf_0F_2 (calculated as for Fig. 3) at Brisbane following Russian explosions on 23.x.61 and 30.x.61.

recorded at ground level by the Brisbane Weather Bureau. These appear to have originated at the explosion site. Figure 14 shows a plot of the pressure changes around this time. These are compared in the same diagram with $h'F_2$ values during the same period. If the ground pressure oscillations and the ionospheric height variations originate at Novaya Zemlya, the speeds of propagation are 342 and 322 m/s respectively, and the wavelength in the ionosphere is about 600 km.

Rose, Oksman, and Kataja (1961) have published ionograms for Sodankyla (30.x.61), 1160 km from the explosion site, showing the ionospheric effects at this station. The authors point out that the first ionospheric effect at 0900 U.T. is 42 min prior to the first microbarograph reading. However, the speed of propagation for this first ionospheric effect is 722 m/s, which is roughly consistent with the speed of 630 m/s calculated from Brisbane ionograms following this explosion, and with the speed of 647 m/s (Fig. 4) for the Johnston I. explosions.

VI. Discussion

Pressure waves travelling with speeds close to the speed of sound in the lower atmosphere have been regularly recorded after nuclear explosions. Yamamoto (1957) lists 18 occasions between November 1952 and April 1957 when pressure waves have reached Japan from both American and Russian

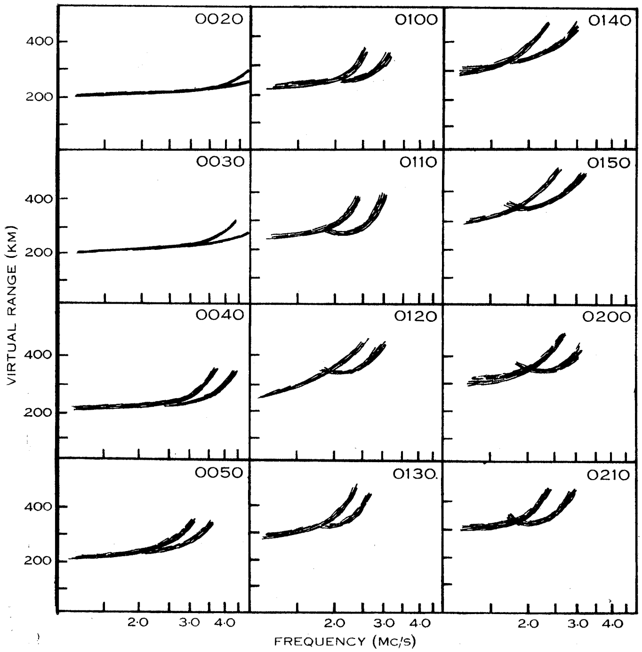

Fig. 13.—Tracings of ionograms at Brisbane (0020 to 0210 inclusive, 31.x.61—local time) following Russian explosion at 1833 (local time) on 30.x.61.

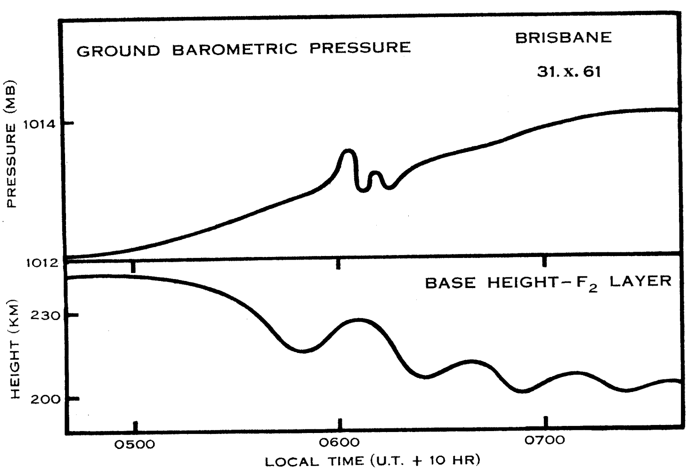

Fig. 14.—Comparison of ground barometric pressure oscillations with $h'F_2$ oscillations at Brisbane around 0600 (local time) on 31.x.61.

explosion sites. The periods of oscillation range from an average maximum value of 2·9 min to an average minimum value of 0·6 min, and the average speed of propagation is 309 m/s.

The average speed of propagation of one of the ionospheric disturbances of 333 m/s (Fig. 4) suggests that the ionospheric irregularities might possibly result from the transit of a pressure wave, travelling in the sound channel provided by the temperature minimum at the 80 km level. Pressure waves propagate at this level with little attenuation and little dispersion (Flugge 1957). Laplace's equation for the velocity of propagation of pressure waves (sound) in the atmosphere is $c=\sqrt{(\gamma RT/M)}$ where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume for the gas concerned, R is the gas constant per mole, M is the molecular weight of the gas, and T is the absolute temperature. The values of γ and M at ionospheric heights are still uncertain (Chamberlain 1961). If reasonable values are chosen say $\gamma=1\cdot4$ and $M=27$ for the 80 km level of the atmosphere, a pressure wave propagating at 333 m/s indicates a temperature of 246 °K. The small difference between the times of arrival at Brisbane of a pressure wave on the ground and an ionospheric disturbance in the F_2 layer (Fig. 14), following the nuclear explosion at Novaya Zemlya (Russia) on 30.x.61, may be of significance to this postulate.

The disturbance which propagates with an average speed of 647 m/s has similar characteristics to that propagating with an average speed of 333 m/s. Another sound channel higher in the atmosphere could be postulated. At this new level pressure waves would travel with greater speeds due to the increase in temperature with height in the lower regions of the ionosphere. Using estimated values of γ and M for around 180 km ($\gamma=1\cdot5$ and $M=25$) the temperature calculated from Laplace's equation is 840 °K.

Evidence exists in the literature for a temperature inversion at about 180 km which could provide the sound channel necessary to fit the ideas proposed here. It has been pointed out (Kallmann 1959 ; Kallmann-Bijl 1961) that there is at this height a discontinuity in the exponential decrease of density with height, suggesting a temperature irregularity, perhaps an inversion. Similar discontinuities exist at the 50 and 90 km levels where temperature inversions exist (Kallmann 1959). A profile of temperature variation with height (at night) suggested from the calculated temperatures for the proposed regions of pressure wave propagation, and the established experimental information (Kallmann-Bijl 1961) is given in Figure 15.

Previous work has shown that the ionospheric irregularities responsible for spread-F echoes, and also the day-time disturbances (Bowman 1960*b* ; Munro and Heisler 1956 ; Heisler and Whitehead 1960) extend through the whole depth of the ionosphere, rather than a narrow belt. It is not inconceivable that pressure waves at a relatively low level (e.g. 80 km) could be responsible for a disturbance which extends up to the F_2 layer.

Hines (1960) postulates the creation of ionospheric irregularities by pressure waves, and mentions the possibility of generation and ducting of the waves in the lower regions of the ionosphere.

The period of oscillation calculated for the ionospheric irregularities for the first spread-F disturbance to arrive at Brisbane is $0 \cdot 8$ min. This period is comparable with the range of periods ($0 \cdot 6$ to $2 \cdot 9$ min) recorded by Yamamoto (1957) for pressure waves recorded on the ground in Japan from nuclear explosions in the Pacific Ocean and in Russia.

The ripple structure of the ionization density contours responsible for the spread-F echoes at Brisbane after the first Johnston I. explosion had a calculated average wavelength of 36 km. However, at other places and at other times, the structure is too big to be identified as spread-F. On these occasions the ripple structure can be identified from the height undulations indicated on the ionograms. Wavelengths as long as 600 km have been indicated in Sections IV and V.

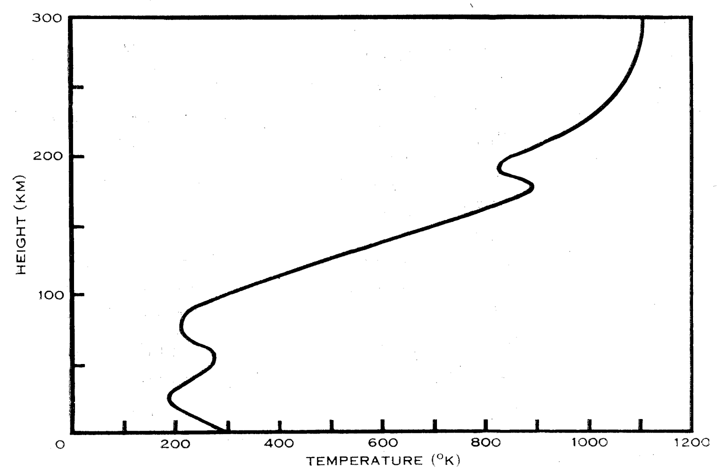

Fig. 15.—Proposed temperature variation with height showing temperature minima at about 30, 80, and 180 km.

Perhaps on these occasions the shorter wavelength components have been preferentially absorbed (Flugge 1957). This could occur for propagation over great distances, or when weaker explosions were involved.

The first disturbance detected after the Johnston I. explosions, giving an increase in Δf_0F_2, seems to be of a different character to the following two. The estimated speed of propagation is about 1666 m/s, but there is a much greater scatter of points than for the other disturbances. This could possibly be a hydromagnetic disturbance. However, if this is the case, the association of the magnitude of the effect with the stations' distance from the conjugate point of the explosion site, rather than the explosion site itself (Fig. 7), would still need to be explained.

Ionospheric storms exhibiting the same characteristics as those found for two of the disturbances detected in this investigation, namely the sudden fall in f_0F_2, height rise, and spread-F conditions, are found to propagate from polar regions at times of magnetic storms. Wright (1961) has found a lower limit for the apparent speed of these disturbances, over a path of 1105 km, of 403 m/s.

This speed is somewhat higher than the 333 m/s found for one type of disturbance following the nuclear explosions.

It seems possible that the bombardment of polar regions by solar particles, at the times of magnetic storms, is effective in producing pressure waves which propagate to lower latitudes causing ionospheric storms as they progress (cf. Hines 1960). The difference in speeds indicated above could possibly be explained by the reported 30% increase in temperature in the ionosphere following disturbed magnetic conditions (Bauer 1960).

VII. Acknowledgments

The author would like to thank Professor H. C. Webster for his assistance in the preparation of this paper. Thanks are also due to the Ionospheric Prediction Service, Brisbane Weather Bureau, and Bureau of Mineral Resources for supplying data used in the analysis. This work forms part of the programme of the Radio Research Board, C.S.I.R.O.

VIII. References

Baird, K. (1956).—*Aust. J. Phys.* **7**: 165.
Bauer, S. J. (1960).—*J. Geophys. Res.* **65**: 1685.
Bowman, G. G. (1960*a*).—*Planet. Space Sci.* **2**: 133.
Bowman, G. G. (1960*b*).—*Planet. Space. Sci.* **2**: 195.
Chamberlain, J. W. (1961).—"Physics of the Aurora and Airglow." (Academic Press : London.)
Cummack, C. H., and King, G. A. M. (1959).—*N.Z. J. Geol. Geophys.* **2**: 634.
Flugge, S. (Ed.) (1957).—"Handbuch der Physik." Vol. 48. p. 455.
Heisler, L. H. (1958).—*Aust. J. Phys.* **11**: 79.
Heisler, L. H., and Whitehead, J. D. (1960).—*J. Geophys. Res.* **65**: 2767.
Hines, C. O. (1960).—*Canad. J. Phys.* **38**: 1441.
Kallmann, H. K. (1959).—*J. Geophys. Res.* **64**: 615.
Kallmann-Bijl, H. K. (1961).—*J. Geophys. Res.* **66**: 787.
McNicol, R. W. E., Webster, H. C., and Bowman, G. G. (1956).—*Aust. J. Phys.* **9**: 247.
Matsushita, S. (1959).—*J. Geophys. Res.* **64**: 1149.
Munro, G. H., and Heisler, L. H. (1956).—*Aust. J. Phys.* **9**: 359.
Rose, G., Oksman, J., and Kataja, E. (1961).—*Nature* **192**: 1173.
Schmerling, E. R. (1958).—*J. Atmos. Terr. Phys.* **12**: 8.
Wright, M. D. (1961).—*Nature* **190**: 898.
Yamamoto, R. (1957).—*J. Meteor. Soc. Japan* Ser. II. **35**: 32.