4) G. R. Ellis: J. Atmos. Terr. Phys. **10** (1957) 302.
5) J. W. MacArthur: Phys. Rev. Letters **2** (1959) 491.
6) C.C.I.R.: Document of the IXth Plenary Assembly, Los Angeles III (1959) 223.
7) I. Kimura: Rep. Ionos. Space Res. Japan **15** (1961) 171.

Discussion

A (Unidentified person): In your Table I showing the estimated intensity of the emissions, you gave the power density of 10^{-20}w/m^2(c/s) for Cherenkov radiation, which was calculated from the emission of individual particles. If you take into account the stimulated emission, you will get much larger power. The approach is to take into account the things you have rejected in your treatment.

Dungey, J. W. (to A): You mean the stimulated emission corresponds to the amplification?

A (to Dungey): Yes, that's really what I mean.

Kimura, I.: It may be an alternative interpretation of the amplification mechanism. My way of thinking is that our proton mechanism is a kind of "anomalous Doppler effect" which was first reported theoretically by V. L. Ginzburg (Soviet Physics USPEKHI **2** (1960) 874–893).

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-1C-P1. Whistlers and VLF Emissions in Connection with the Earth Storms

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Fundamental features of whistlers and VLF emissions including hiss, dawn chorus and others are briefly reviewed and important characteristics in disturbed states, which have been reported by the papers presented in this symposium as well as by other papers, are studied. The related theories to interpret the phenomena are surveyed, and discussions are given on some important characteristics of the phenomena. Some suggestions on data reduction and on possible experimental studies by means of satellite are also proposed.

§1. Fundamental features

The very low frequency (VLF) radio phenomena which are treated in this paper contain a series of natural radio noises at frequencies between 1 to 30 kc, known as "Whistlers," "Hiss," "Dawn Chorus" and similar rising and falling tones. For the sake of convenience whole phenomena are classified into three groups. The first group (W) includes the whistlers, the second group (C) includes the dawn chorus, hooks, quasi-horizontal and falling tones and the third group (H) includes the hiss, which is called "Noise burst" or "Noise Storm" by Ellis and others. The second group in this paper is conventionally represented by "Chorus."

Following is a summary report on fundamental features of the VLF phenomena, which have been revealed mainly by systematic observations carried out in the U.S.A. and in Australia and New Zealand.

1) Time duration. This is short in case of W and C, say, the order of 0.1—1 second, while that of H is long, say, the order of

hours.

2) Frequency band. This is usually between 1 and 8 kc, sometimes extends to 30 kc or more for all groups.

3) Frequency-time characteristics. This is obtained by analyzing a recorded tape by Sonagraph. The time variation of frequency as analyzed by Sonagraph is discrete for *W* and *C*, while that of *H* is widely spread. The frequency falls with time for *W* except the "Nose whistlers," and *C* has various kinds of frequency changes, as shown in Fig. 1. The frequency band of *H* does not vary much with time. (See also Fig. 1.)

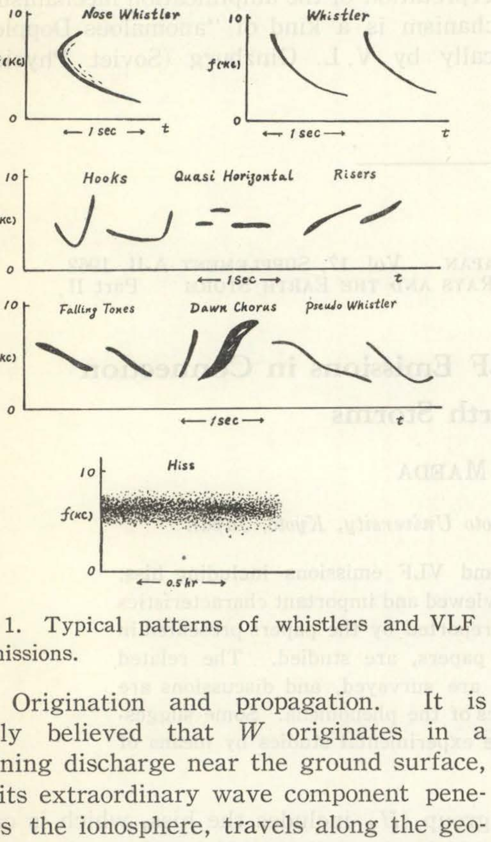

Fig. 1. Typical patterns of whistlers and VLF emissions.

4) Origination and propagation. It is widely believed that *W* originates in a lightning discharge near the ground surface, and its extraordinary wave component penetrates the ionosphere, travels along the geomagnetic line of force through the exosphere and comes down again to the ground in the opposite hemisphere. A direct experimental evidence of exospheric propagation of *W* has been clearly demonstrated by Heppner's paper[1] in this symposium, in which he showed that a receiver borne in the Vanguard III satellite observed many whistlers at the height of 510 to 3750 km. Although there is no such direct evidence yet as in the case of *W*, we believe that *H* and *C* originate in some places in the exosphere, travel in the same mode as *W* (whistler mode) and reach the ground surface. And the whole phenomenon is purely electro-magnetic.

§ 2. Characteristics in disturbed states

The frequency of occurrence of *W*, *H* and *C* has been studied and reported by Yoshida[2], Outsu[3] and Legrand[4] in this symposium and also McK. Allcock[5], Crouchley[6], Ellis[7] and Helliwell[8] had published their papers on this topic.

1) The diurnal variation of occurrence frequency. Fig. 2 was reproduced from the

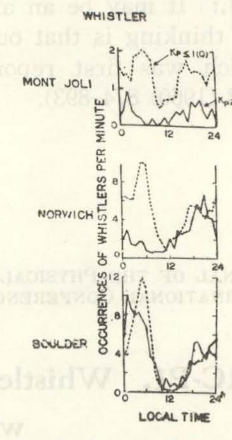

Fig. 2. Diurnal variation of occurrence of whistlers (after Yoshida).

paper of Yoshida[2]. From the Figures shown by dotted curves we can observe a peak at early morning and a submaximum in the evening for *W*. The result is roughly the same as that of Crouchley[6], who studied the vairation of *W* for winter, summer and other months. As for *C*, McK. Allcock[5] found a peak from 3 to 6 hrs in the morning. (Probably this includes the case of disturbed state.) Dotted curves in right hand side of Fig. 3, which was reproduced from Yoshida's[2] paper, show non-existence of any distinct peak in general except in the case of high latitude stations, in which a peak can be seen near noon in the morning side. As for *H*, dotted curves in left hand side of Fig. 3 show a similar tendency to that of *C*.

In magnetically disturbed states, which are defined by K_p larger than 5, the early morning peak can be seen in solid curves in Fig. 3 (*C* and *H*). This tendency is especially clear for *C*. The local time of the peak in

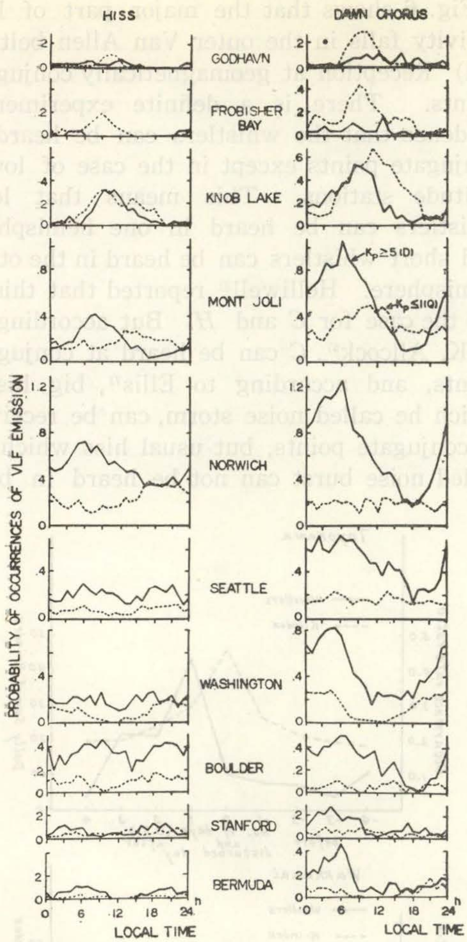

Fig. 3. Diurnal variation of occurrence of hiss and chorus (after Yoshida).

occurrence frequency depends upon the geomagnetic latitude of the station. As for *W*, the early morning peak becomes less predominant in disturbed states and it moves near midnight, as seen in solid curves of Fig. 2. According to the results by Ellis[7] the diurnal trend of *H* is more or less similar to that of Yoshida. The peak in case of *H* is clear only at high latitude, and this can be said a difference between *H* and *C*.

2) Seasonal variation in occurrence frequency. There are a clear maximum in winter months and a submaximum in summer months for *W*, and this summer submaximum can be attributed to frequent occurrences of long whistlers. According to Helliwell[8] chorus activity is maximum in April and May and minimum in November and December in northern hemisphere, but McK. Allcock[5] did not find any distinct maximum or minimum.

3) Latitude dependence of occurrence frequency. The distribution of occurrence frequency plotted against geomagnetic latitude has a peak at 50°—55° for *W*, at 55°—60° for *H* and at 60°—65° for *C*. (See Fig. 4 and later description.)

We have to notice that the latitude (50°—55°) of peak activity of *W* is generally deviated from the zone of maximum activity of thunder storm. In this connection attention should be paid to the important result of experiment reported by Heppner[1] in this symposium. According to the observation made by Vanguard III, the occurrence frequency at low altitude over the equator is just as great as at other locations. It is supposed that the effect of polar creep in the propagation of *W* (discussed later) may be partly responsible to the above deviation of the peak and/or some screening mechanism may be working on the downward penetration through the ionosphere at lower latitudes.

Fig. 4 shows the latitude dependence of occurrence frequency of *C* and *H* in undisturbed states (circles and dotted curves),

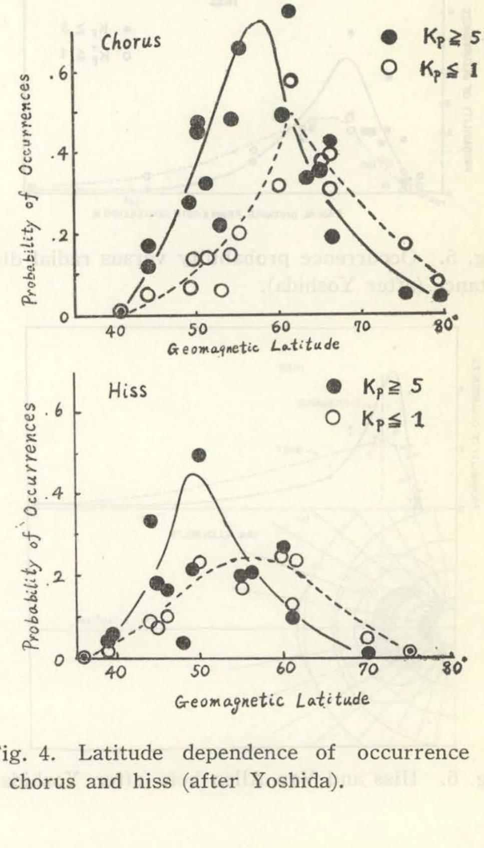

Fig. 4. Latitude dependence of occurrence of chorus and hiss (after Yoshida).

which has been worked out by Yoshida[12]. The peaks for both cases deviate to lower latitude in disturbed states. Fig. 5 is similar plots, in which the abscissa is somewhat different. The abscissa is the distance from the ground surface to the point at which the line of force starting from the station cuts the equatorial plane. The line of force was determined from Vestine's analysis of permanent geomagnetism. The plotted points are less scattered for the case of C in comparison with the curves in Fig. 4. Yoshida interprets that the VLF emission of the type C travels closely along the line of magnetic force.

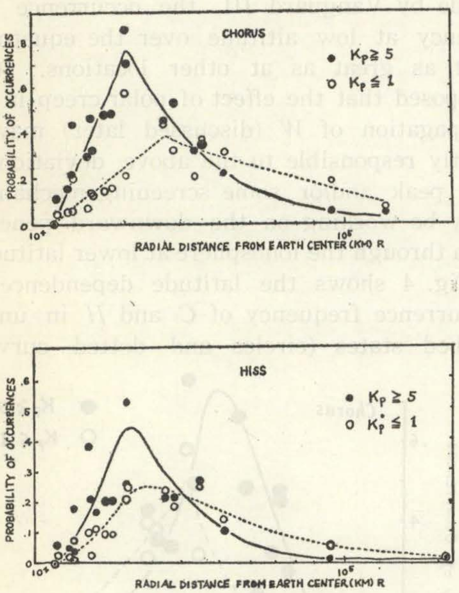

Fig. 5. Occurrence probability versus radial distance (after Yoshida).

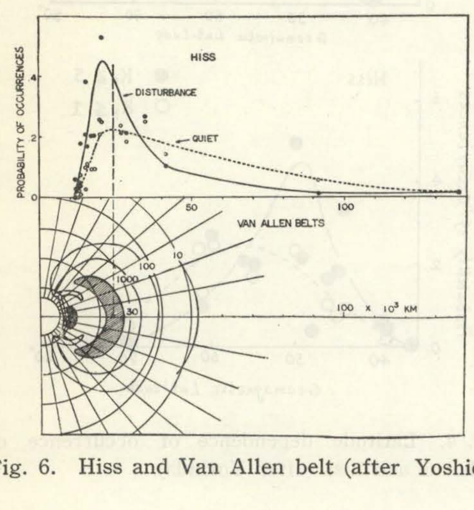

Fig. 6. Hiss and Van Allen belt (after Yoshida).

Fig. 6 shows that the major part of hiss activity falls in the outer Van Allen belt.

4) Reception at geomagnetically conjugate points. There is a definite experimental evidence that the whistlers can be heard at conjugate points except in the case of lower latitude stations. This means that long whistlers can be heard in one hemisphere and short whistlers can be heard in the other hemisphere. Helliwell[8] reported that this is not the case for C and H. But according to McK. Allcock[5], C can be heard at conjugate points, and according to Ellis[7], big hisses which he called noise storm, can be received at conjugate points, but usual hiss which he called noise burst can not be heard in both

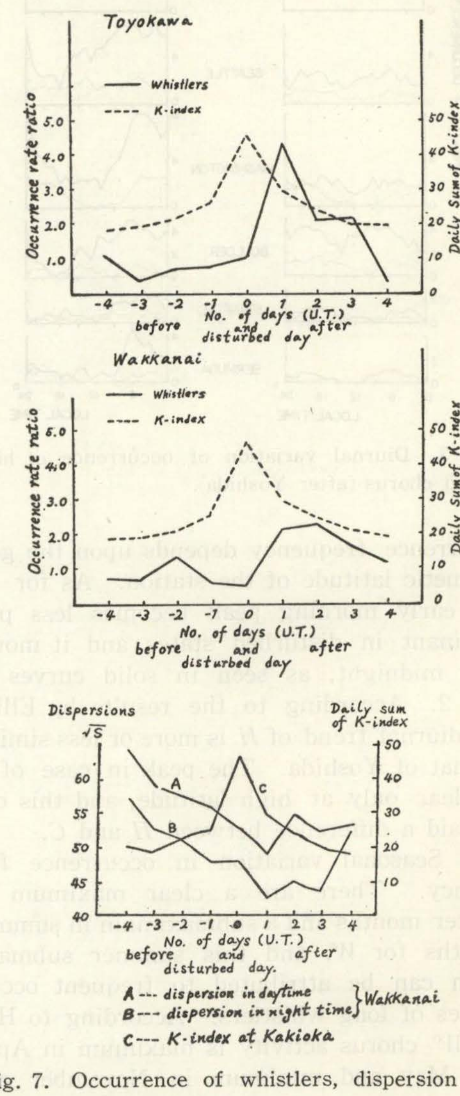

Fig. 7. Occurrence of whistlers, dispersion and K index (after Outsu).

hemispheres at the same time. The result is somewhat conflicting. One may suppose that the reception at conjugate points depends upon the strength of the VLF emissions, but it needs further investigations.

5) Relation with geomagnetic storms. In the case of W, the relation between K index and occurrence frequency is somewhat different, depending upon the way of statistics. Fig. 7 is the result of statistics made by Outsu[3]. The peak of occurrence frequency and the minimum of Dispersion lag one day behind the maximum K. And this tendency becomes less distinct as the station goes up to higher latitude. Occurrence frequency was plotted against K_p index by Crouchley[6] and Yoshida[2]. The relation obtained by Crouchley does not show any clear tendency, but that by Yoshida shows a peak at a certain value of K_p, which is relatively low, and the peak moves toward much less value of K_p with increase of latitude. Yoshida interprets that the increase of absorption of whistler waves at greater K_p will be the cause of less frequent occurrence of the phenomena.

Fig. 8 was given by Yoshida[2] to show the

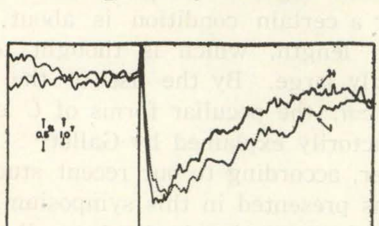

Fig. 8. Geomagnetic and cosmic ray storms and occurrence of chorus and hiss (after Yoshida).

relation between the geomagnetic storm and occurrence frequencies of H and C. The uppermost curves show typical examples of horizontal magnetic intensity and cosmic ray intensity. The chorus activity reaches its maximum about one day after the S.C. Similar tendency can be seen for H. According to Ellis[7] and Legrand[4], the hiss starts to become frequent about 9 hours in average after the S.C. and reaches the maximum occurrence in the main phase of the storm, that is, 18 hours in average after the S.C. Generally speaking, the activities of H, C and W reach their maximum near the end of main phase of geomagnetic storm, continue to be high in the recovery phase and decrease gradually.

6) Relation with other disturbance phenomena. According to Ellis[7], the hiss recorded during daytime is associated with auroral activity and occurs also in association with the night airglow (6300Å). He located sometimes the sources of H with limited geographical size and found that the commencement of the hiss coincided with bay type geomagnetic variation. He also found a relatively close association between H and Pc pulsation with periods between 10 and 60 minutes, but the relation with magnetic oscillations with periods less than 1 min. was not close.

§ 3. Survey of related theories

1) Propagation path. After Storey[9] published his original theory on the propagation of W, a detailed theory was worked out by us[10] to calculate the path through the exosphere consisted of smoothly distributed steady plasma, and then based on Haselgrove's principle an extensive calculation of the path was carried out by Yabroff[11]. By these studies it was established that the waves of W originated at lower latitudes suffer the so-called polar creep in their propagation and those starting from higher latitudes suffer the so-called equatorial creep. (See Figs. 9 and 10.) Discovery of the nose whistler was very useful for estimating the electron density distribution. In the meantime a theory was worked out by Yabroff[11] on the path calculation in a non-smooth plasma, in which the electron density is enhanced along geomagnetic line of force. This theory has been proved to be

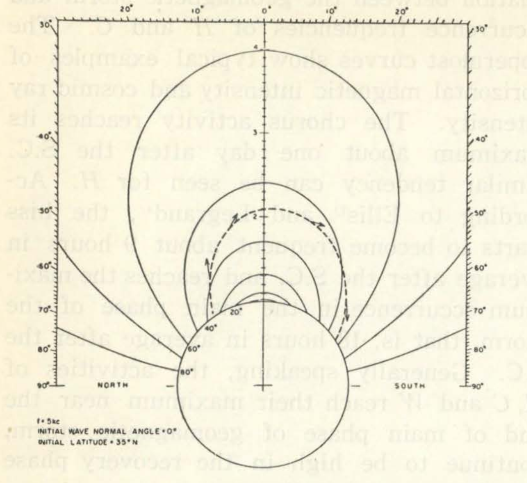

Fig. 9. Ray path initiating at 35°N latitude (after Yabroff).

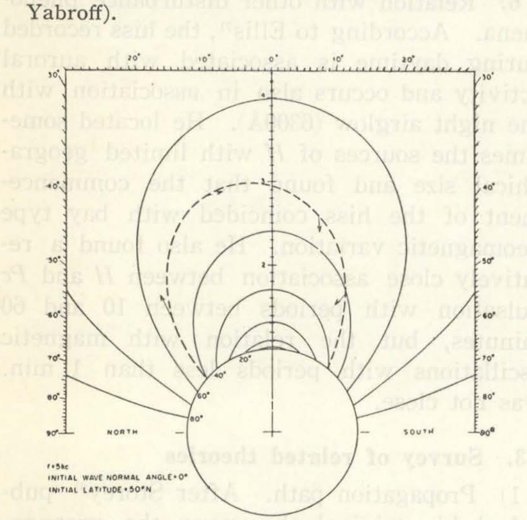

Fig. 10. Ray path initiating at 50°N latitude (after Yabroff).

effective in showing that the waves are trapped within the enhanced column and no creeps occur practically. (See Fig. 11.) Experimental evidence to the existence of such ionization columns in the lower exosphere has been demonstrated by Australian investigators.

2) Generation and amplification. As for the possible origin of H and C, a number of alternative hypotheses has been investigated, and it is said that the Cherenkov radiation[12] can yield the largest energy. But this origin is still very weak and needs a great degree of amplification in order to be detected on the ground. The amplification mechanism as in a travelling wave tube has been proposed

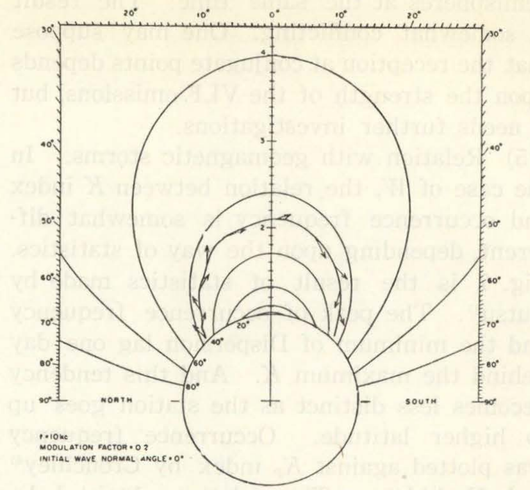

Fig. 11. A field-aligned column model (after Yabroff).

and studied by Gallet and Helliwell[13]. The theory concerns a longitudinal coupling between the electron stream and the wave. According to this theory the condition of amplification is that the phase velocity (v_{ph}) of the wave is nearly equal to the velocity (u) of the electron stream flowing in a steady plasma. The degree of amplification estimated under a certain condition is about 2 db per wave length, which is thought to be surprisingly large. By the use of the condition $v_{ph} \simeq u$, the peculiar forms of C could be satisfactorily explained by Gallet[14].

However, according to our recent study[15], which was presented in this symposium, we have found that a longitudinal coupling as stated above would not be capable to act as amplifier in the exospheric state as considered in our problem. But in this case the space charge waves can grow up as a result of bunching of electron density. We have found as an alternative that the cyclotron motion of protons in a plasma stream transversally coupled with the wave can yield a certain degree of amplification, say, at most 20 db for the whole length of possible coupling. The condition for the efficient coupling is so much the same as in the former theory ($v_{ph} \simeq u$). If this is the case, we have to search for a source which is much more powerful than the Cherenkov radiation or its like.

In this connection we notice that the background noise level in the exosphere must be considerably high, because the space is continuously fed with the atmospheric noise on the ground.

3) Controlling factors. Besides the above theories we have to consider one point, which is very important for understanding how the VLF waves (*W*, *C* and *H*) come down to the ground with sufficient intensity. The conditions which control this problem are (i) absorption in the ionosphere, (ii) propagation in the medium between the ground and the ionosphere and (iii) penetration through the ionosphere. Among these three, the most important is the last problem. The refractive index for the waves propagating in the whistler mode, which is unity in the space below the ionosphere, increases abruptly to a large value as the waves emerge into the ionosphere. Such a rapid change occurs again at the boundary between *E* and *F* layers, although not so big as at the lower boundary of the *E* (or *D*) layer. In these circumstances one can not expect the penetration of the total energy, but rather a partial reflection of greater energy takes place inevitably. The situation will be roughly the same, when the waves come down from above. The problem is much complicated, when we take into account the effect of the earth's magnetic field, that is, the anisotropy of the ionosphere. Generally speaking, the directions of the wave normal and the magnetic field will be the controlling factors, and only when these situations are favourable, the wave can pass through the ionosphere without any serious loss of energy by partial reflection.

§ 4. Discussions and future problems

1) Significance of field aligned ionization and fast plasma flow. When we assume a smooth distribution of electron density in the exosphere, the direction of the wave normal is almost fixed, as the geomagnetic field construction is also fixed. According to Yabroff's calculation, the wave normal direction at the end of the wave path, that is, at the boundary between the exosphere and the ionosphere, can not be arbitrary and this direction is not always favourable for an efficient penetration. The only cause that can change the wave normal to some extent is the ionization column which is aligned in geomagnetic field line. And if the plasma in this column moves very fast, it can amplify the VLF radio waves (*W*, *C* and *H*).

Thus the rôle played by the field aligned ionization will be very important for an efficient penetration downward through the ionosphere. The existence of field aligned ionizations concerns the latitude dependence of occurrence frequency of *W*, *C* and *H* in disturbed as well as undisturbed states, in other words, the reception of *W*, *C* and *H* depends partly upon the situation that the ionization enhancement is frequently and easily produced on the field line connecting with the station. The existence of fast flow of plasma along the field line, which is expected to intensify VLF waves, concerns the possible cause of generation of sporadic *E*, spread *F*, bay type magnetic disturbance, auroral activity and geomagnetic pulsation, which sometimes take place in association with the hiss. This bears also a significance on the question whether *C* and *H* can be heard at conjugate points or not.

2) Difference between *H* and *C*. Although in the theoretical study on the propagation, generation and amplification of *H* and *C*, the both phenomena have been treated in one and the same way, we have to notice that there are great differences between them, such as differences in their time duration and frequency-time characteristics. This problem is a very important point to be studied further. In this connection it may be added that the morning peak in the diurnal variation of occurrence frequency of *C* and its change with latitude means, according to McK. Allcock, that the positively charged particles, presumably the protons, will be the cause of *C*.

3) We have one more difficulty, which will be left for future investigations. The question is how we can explain the time coincidence of maximum occurrence frequency of *H* and *C* with the end of main phase through the eariler stage of recovery phase in geomagnetic storm.

4) Data reduction. We are now in the stage to go into more detailed study of individual behaviours of *W*, *C* and *H*. And in order to do this satisfactorily, we have to have data reduced in more detail, besides the usual informations on dispersion of *W* and on occurrence or non-occurrrence of *W*, *C*

and H. Desirable data which can be reduced from the records, will be the type of waves, exact time of occurrence, frequency characteristics and band, field strength, and, if possible, the level of back ground noise.

5) Satellite experiments. The experiment made by Vanguard III satellite, which has been reported by Heppner in this symposium, has been found to be very important. Besides the above, an experiment with a transmitter at VLF borne in a satellite will be also very useful for the verification of related theories on propagation and penetration. Experimental investigation on field aligned ionization by means of a certain electron probe borne in a satellite is also desirable.

References

1) J. P. Heppner et al.: Proc. Int. Conf. Cosmic Rays and the Earth Storm (1961) II-1C-3.
2) S. Yoshida and T. Hatanaka: ibid. II-1C-2.
3) J. Outsu and A. Iwai: ibid. II-1C-4.
4) Y. Corcuff and J. P. Legrand: ibid. II-1C-1.
5) G. Mck. Allcock: Australian J. Phys. **10** (1957) 285-298.
6) J. Crouchley: Australian J. Phys. **14** (1961) 22-39.
7) G. R. A. Ellis: J. Geophys. Res. **65** (1960) 839-843, 1705-1710; **66** (1961) 19-23, Planet. Space Sci. **1** (1959) 253-258; Nature **184** (1959) 1307-1310, 1391-1393; **186** (1960) 229.
8) R. A. Helliwell: J. Res. NBS **64** D (1960) 642-654.
9) L. R. O. Storey: Phil. Trans. Roy. Soc. A, **246** (1953) 113-141.
10) K. Maeda and I. Kimura: Rep. Ionos. Res. Japan **10** (1956) 105-123.
11) R. L. Smith, R. A. Helliwell and I. W. Yabroff: J. Geophys. Res. **65** (1960) 815-823.
12) G. R. A. Ellis: J. Atmos. Terr. Phys. **10** (1957) 302-306.
13) R. M. Gallet and R. A. Helliwell: J. Res. NBS **63** D (1959) 21-27.
14) R. M. Gallet: Proc. IRE **47** (1959) 211-231.
15) K. Maeda and I. Kimura: Proc. Int. Conf. Cosmic Rays and the Earth Storm (1961) II-1C-5. I. Kimura: Rep. Ionos. Space Res. Japan **15** (1961) 171-191.

Discussion

Singer, S. F.: If only protons can be the source of VLF emissions, how can one explain the positive correlation with the outer radiation belt (which contains mainly electrons).

Maeda, K.: Your question points out a very important problem, which needs further careful studies. In connection with your question I may briefly summarize the results of our recent theoretical investigation. We found a possibility of amplification of VLF radio waves by proton cyclotron motion transversally coupled with the radio waves. The condition for effective amplification is v_{ph} (phase velocity of the wave) $\simeq U$ (proton stream velocity), and this relation enables us to explain some important characteristics of VLF phenomena, especially peculiar frequency-time characteristics, according to the study of Gallet.

As for the rôle of electron stream, we have found so far that from the electron stream a longitudinal space charge wave originates and this wave may spatially grow up. Then it will be expected that this space charge wave can emit radio waves when the space charge wave comes across certain irregularities or discontinuities of the medium, such as the lower boundary of the ionosphere or the boundary between E and F layers. However, in this case of space charge wave, there is no requirement for the condition $v_{ph}\simeq U$, which is important for interpreting the characteristics of VLF phenomena, and furthermore we cannot find any condition to control the frequency band of VLF waves, which is limited within a certain definite band as observed by experiments.

Campbell, W. H.: (1) I would like to bring the speaker's attention to a rather unique type of VLF emission which was omitted in his discussion. This is the "rhythmic hiss" or "surf" phenomenon which has been recorded in the auroral zone and simultaneously at close to conjugate field points on the earth. Mr. R. Gallet of NBS Central Propagation Laboratory in U.S.A. has reported this unique emission and is presently studying the phenomenon.

(2) I investigated the relation of hiss to micropulsations of 5—30 sec. period for 1

year's data at College, Alaska, and could find no unique relationship either for particular events or on a gross scale. The correlation coefficient between occurrences of the two phenomena was about 0.3 or 0.4. This seems to contradict the reported relationship in your paper.

Maeda: (1) Yes, I know the "surf," which was reported by you in J.G.R. I hope that this phenomenon will call attention of other investigators and observations will be made at various parts of the world.

(2) Prof. Ellis reported in his paper in J.G.R. Vol. 65 that quasi-sinusoidal magnetic oscillations with periods between 10 and 60 min. occurred either before or during noise bursts on 14 occasions and were recorded only 3 times without a corresponding noise burst, and noise bursts were recorded 8 times without any sort of micropulsations and 4 times in association with those having periods between 60 and 75 seconds. As for the micropulsations with periods less than 60 seconds, no definite correlation could be found with noise bursts. This last result will be consistent with your results.

Kimpara A.: Here I would like to make a short comment to this question. We studied and discussed "whistlers and VLF emission" fully at the 13th General Assembly of URSI held in London last September, and determined to study specifically the dispersion of whistlers which suggests powerfully the distribution of electron density and magnetic field intensity in the exosphere.

Until recently we studied the dispersion statistically, but I think it is the time to study the phenomenon individually. As contributions from the scientists on cosmic rays and geomagnetism will be greatly useful to the development of the study on these problems, I hope that all the participants here are kind enough to help URSI, by their special contributions.