acta phys. slov. 35 (1985), No. 3

INCOHERENT CERENKOV RADIATION AS A SOURCE OF VLF HISS

S. S. DE[1], J. BANDYOPADHYAY[1], Calcutta

The present paper mainly embodies the investigations on VLF hiss in terms of Cerenkov mechanism. This work has been initiated with the object of examining the different models in the light of experimental observations made through ground-based as well as satellite-based equipments. The latitude dependence of the observed spectral densities of VLF hiss emissions has been presented graphically.

НЕКОГЕРЕНТНОЕ ЧЕРЕНКОВСКОЕ ИЗЛУЧЕНИЕ КАК ИСТОЧНИК ВЕСЬМА НИЗКОЧАСТОТНОГО СВИСТА

В статье приводятся результаты исследований весьма низкочастотного свиста при помощи черенковского механизма. Работа проведена с целью проверки различных моделей на основе экспериментальных наблюдений, которые были осуществлены при помощи оборудования, установленного на земле и на спутнике. Приведена также графическая зависимость наблюдаемых спектральных плотностей излучения весьма низкочастотного свиста от географической широты.

I. INTRODUCTION

The phenomena of whistlers and related emissions have been well understood from the experimental as well as the theoretical standpoint in a comprehensive manner through the works of many authors [1—25].

Whistlers involve a broad frequency range from zero up to the electron gyrofrequencies, which include ion-cyclotron resonances, ion-ion hybrid resonances, cut-off frequencies etc. Within this frequency range, there are irregular and non-specific emissions, the true nature of which was partly recognized in 1957. Gradually it has been understood that a substantial portion of these emissions is due to the excitation of the streaming high speed ionized particles moving through the exosphere. Although the propagation mode of these emissions is similar to whistlers, these VLF emissions are different from the standpoint of the origin and

[1]) Centre of Advanced Study in Radio Physics and Electronics, University of Calcutta, 1, Girish Vidyaratna Lane, CALCUTTA-700 009, India.

source of energy. These broadband modes are known as hiss, which sounds like thermal noise. Hiss is observed most frequently in the auroral zones. Apart from auroral hiss, midlatitude and low latitude hisses are also observed. The satellite measurement data [26, 27] revealed that the VLF hiss covers the frequency range of the order of 1 to 500 kHz. In the Antarctic region hiss emission up to several hundred kHz is observed [28]. A midlatitude hiss occurs below 10 kHz under normal conditions. Auroral hisses are observed in steady and impulsive forms among which the latter is rare. A midlatitude hiss seems to be associated with discrete emissions. It is observed that the intensity variations of a VLF hiss and aurora are closely correlated [29, 30]. A low latitude hiss, below 30° latitude is found to be less intense than that of mid-and high latitudes.

The study of the VLF emission and mode of propagation reveal certain properties of the magnetosphere and regions of particle precipitations. The dynamic properties of the exosphere may also be explored through such studies. Various attempts have been made to explain the hiss phenomena through different mechanisms, viz., the Cerenkov radiation, the Doppler-shifted cyclotron radiation, travelling wave, resonance interaction etc. So far the incoherent Cerenkov mechanism has been considered to be the most probable cause for the generation of VLF hisses. The present paper critically reviews the various theoretical attempts to explain the VLF his phenomena observed through ground-based experiments and satellite-based experiments at different latitudes.

The variation of spectral power density with geomagnetic latitude has been presented graphically. Scope for further investigations is also suggested due to certain discrepancies between the results of the theoretical model and experimental observations.

II. RESULTS OF EXPERIMENTAL INVESTIGATIONS

A good number of investigators [26—28], [31—35] reported the hiss observations from very high latitude regions to very low latitude regions through ground-based and satellite-based equipments. VLF hiss phenomena have been characterized through the nature of occurrence, cut-off frequency, spectral power density and variation of intensity with increasing frequency. Steady and also impulsive types of hisses are observed from auroral regions. Midlatitude hisses are found to be associated with discrete emissions. Low latitude hisses are also observed, they yield relatively much less intensity than those of midlatitude and high latitude phenomena.

Observations of the wide band hiss in the frequency range 4—10 kHz made at 13 different stations in both hemispheres up to 1965 have been reported in detail [36]. Later a large number of experiments have been installed, the results of which deserve special significance. Using INJUN 3 data, Gurnett [33] analysed a broadband VLF hiss from about 4 kHz to above 10 kHz. He found that the frequency spectrum of the VLF hiss is a typically flat spectrum with a distinct lower-frequency cut-off which is often found to have a more or less symmetric latitude variation centred around a region of intense electron precipitations. Observations of high latitude hiss emissions above 1 kHz through the Byrd Station, OGO2 satellite, have been presented by Jorgensen [28]. He analysed the variation of spectral density as a function of frequency.

Burtis and Helliwell [37] reported certain characteristics of the VLF hiss through the analysis of OGO1 and OGO3 data. Russel and Holzer [38] from OGO3 data identified two types of hiss in the frequency range 0.1 to 1 kHz. Among those, one category occurs inside the plasmasphere while the other is outside of it. Characteristic variations of these emissions with time and region have been reported, some of which are consistent with the emission due to gyroresonance instability. Employing a particle spectrometer via the ISIS-I satellite, Heikilla [39] observed electron fluxes in the energy range 10 eV—10 KeV in the low latitude topside ionosphere. Moreover, utilizing ISIS-I satellite data, James [40] observed that the waves have a strong correlation with the precipitating soft electrons in the polar region, having their propagation direction near the electrostatic resonance cone of the whistler mode. Laaspere et al. [26], using OGO6 data, estimated the peak flux for the VLF hiss which agreed with the measurements of Gurnett and Frank [27].

A study of an auroral zone VLF hiss and low energy charged particle observation with the INJUN 5 satellite has been made [27]. The results offer a direct verification of the association between an auroral zone VLF hiss and intense fluxes of electrons with energies of the order of 100 eV to several KeV. Mosier and Gurnett [35] also utilized the same data and reported a spectrogram showing the electric and magnetic fields of a VLF hiss during the passage of the satellite near an auroral arc. They reported the time for a maximum electron flux and maximum VLF hiss emissions. Gurnett and Frank suggested the generation region of the hiss which is at an altitude of about 5,000 to 10,000 kms.

The occurrence of VLF emissions at low latitudes has been detected through the Ariel 3 and the Ariel 4 satellites by Bullough et al. [41]. The intensity of emission was found to be less than that at mid- and high latitudes. A similar type of observation has also been reported [42]. Bullough et al. [43] analysed Ariel 4 satellite data thoroughly. They studied the wave particle phenomena within the magnetosphere through different measurements. Emissions coming from the magnetospheric energetic charged particles into the ionosphere and the latitude variation of the VLF emission at different frequencies have been discussed by them.

A simultaneous recording of different types of whistler and the VLF hiss at a low latitude ground station at Srinagar (geomag. lat., 24°10′ N) was reported by

Khosa et al. [44]. A VLF hiss has also been recorded at Agra (geomag. lat., 17°12′ N) [44] of a bandwidth 5 to 7 kHz unlike the broadband width of the VLF hiss in the auroral region.

III. THEORETICAL BASIS

Among various mechanisms that have been proposed to explain the VLF and LF emissions discussed in the previous section, the Cerenkov mechanism deserves special attention of workers in this field. The theoretical investigations into the problem of Cerenkov radiation from the charged particle spiralling within a magnetoplasma has been made by many authors [45—51] using different mathematical techniques. The motion of the electrons produces an asymmetric polarization of the medium. The polarized field emits radiation because the anisotropic and dispersive medium allows constructive interference of the field for a particular angular and frequency distribution. The possibility of the Cerenkov mechanisms as a source of a VLF hiss is suggested immediately after the detection of these phenomena by Ellis [52]. Several attempts have been made to explain the phenomena on the basis of an incoherent Cerenkov radiation from energetic particles in the magnetosphere. Earlier, it was found that the calculated power was several orders of magnitude below the observed power. This discrepancy between theory and observation was found to be prominent [53, 54]. Under the circumstances, with the advent of various better experimental observations different theoretical models have been devised to study the phenomena. It is concluded that the incoherent Cerenkov mechanism may be the fundamental source for the generation of a hiss. Different models are of special interest and will be discussed in the following section.

Mansfield [53, 55] formulated the problem of radiation from a charged particle moving a cold, collisionless magnetoplasma through the Fourier transform method and obtained an exact solution. In the results of Mansfield, although they were capable for application to the emission of the Cerenkov radiation in the upper atmosphere by auroral particles approaching the earth, the calculated power was not in agreement with that of the observed results. Liemohn [54] worked out the theory of the VLF emission in a dispersive and anisotropic dielectric medium through the Hamiltonian approach. In his work, he predicted the Cerenkov radiation from electrons over a limited band of non-relativistic energies. Jorgensen [28] determined gyrofrequency and plasma frequency of thermal electrons and ions. He derived the distribution function of energetic electrons from various realistic models introduced earlier. These parameters have been incorporated to his model of the incoherent Cerenkov mechanism. Jorgensen utilized the Mansfield model in the auroral hiss in the whistler mode of propagation and calculated the power produced at frequencies below the plasma cut-off and below the electron cyclotron resonance as a function of particle density, pitch angle and altitude. The peak intensity was found at 10 kHz. The results show some similarity with the noise spectra observed from the Byrd Station and from the OGO2 satellite. This confirmed more or less the explanation of the high latitude VLF phenomena in the light of the incoherent Cerenkov radiation.

Rycroft [56] summarized the phenomena of the VLF emission and their possible emission mechanism. A comprehensive list of references has been given in his paper and later in the work of Taylor and Shawhan [57].

Based on the information [27, 35] Lim and Laaspere [58] reexamined the possibility of the incoherent Cerenkov radiation as a source of the VLF hiss, particularly from electrons with an energy less than 1 KeV. In their work they obtained the peak spectral power density at the frequency of 70 kHz at 100 eV unlike the previous investigators. From their analysis the intensity was found to decrease both at lower and higher frequencies. Lim and Laaspere found that the electrons in the range 100 eV to 1 KeV contribute in excess of two orders of magnitude more to the intensity of the VLF hiss than the electrons in the range of 1 KeV to 10 KeV. They suggested that the decrease in power at lower frequencies may be explored by the coherent or partially coherent Cerenkov mechanism.

Through the analysis of the ISIS I data, James [40] computed the absolute intensity of the hiss by using the observed soft electron flux densities assuming the incoherent Cerenkov mechanism. Following James [40], Taylor and Shawhan [57] investigated the incoherent Cerenkov mechanism for hiss phenomena through a complete guided wave propagation model. The peak intensity in their results occurred at 10 kHz. They presented a more detailed calculation of the VLF hiss power, field and spectra. They also modified the formula of Mansfield to include collisions as a dissipative mechanism in order to limit realistically the emitted power and to estimate the spatial attenuation of the propagating waves. In their analysis, the VLF hiss event and an energetic particle spectrum observed simultaneously with the INJUN 5 satellite have been compared. The power and fields for the incoherent Cerenkov radiation are seen to be two orders of magnitude below the observed VLF hiss values, although the spectral shapes were similar. To explain such a situation they predicted the mechanism of a partially coherent or amplified Cerenkov source located in the altitude range of 3,000 km to 10,000 km. Noda and Tumao [59] critically examined the model dependence of differential power spectra from the incoherent Cerenkov radiation. They analysed the results of Jorgensen [28], Lim and Laaspere [58] and Taylor and Shawhan [57]. Due to the deficiency in the magnitude of the power, the waves from low energy electrons will not be purely electromagnetic and for this reason they predicted some conversion processes from electrostatic to electromagnetic waves in the downward propagation. They proposed that the dispersion of the whistler mode in

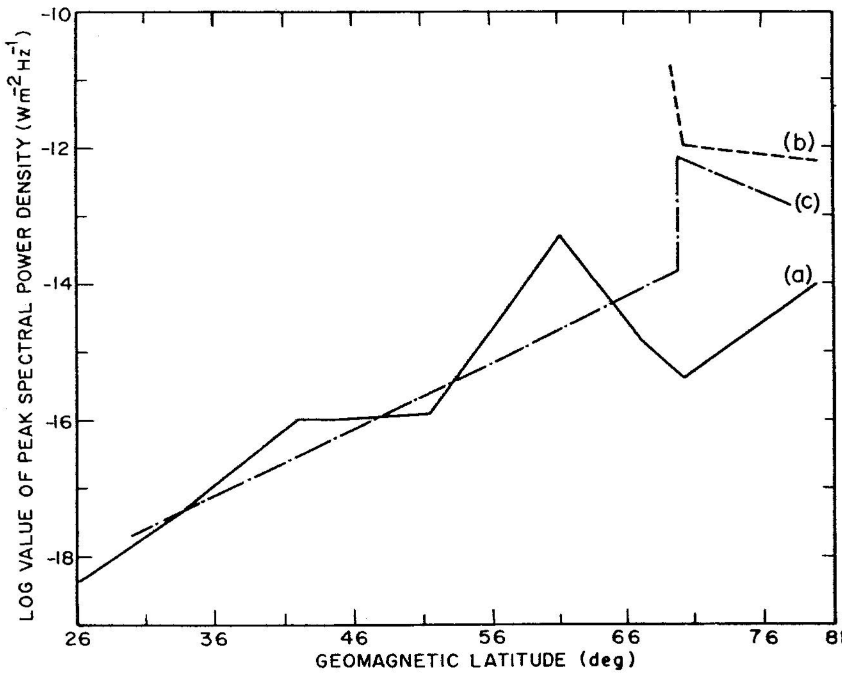

Fig. 1.

a finite temperature plasma may provide such a conversion mechanism. In their paper, they remarked that both the induced emission and the plasma inhomogeneity together with the spontaneous Cerenkov emission are to be considered in the method of analysis to explain the VLF emission.

Attempts have been made to explain the low latitude VLF emision through the Cerenkov radiation from low energy electrons [41], [60—63]. Intensity calculations for low latitude VLF emissions have been made by Prakash et al. [64], who considered the incoherent Cerenkov mechanism as a possible source and found that the final intensity at 30° latitude agreed nearly with the satellite measurements. Utilizing Mansfield's theory in their investigations Prakash et al. showed that the intensities for 100 eV to 1 KeV electrons are slightly greater than the experimental observations of Iwai et al. [65], Ondoh and Isozaki [42]. Their analysis revealed that the low latitude VLF emission may be thought of to be generated through the Cerenkov mechanism.

Taking into account the variation of peak spectral density with geomagnetic latitude, different graphs have been drawn (Fig. 1). The graph (a) is obtained using the results of ground-based experiments [36] and the graph (b) is obtained through the INJUN 5, ALOUETTE 2, OGO 2 satellite-based results. The results of theoretical investigations [28, 57, 58, 64] have been indicated in graph (c). A portion surrounding 70° latitude is associated with the phenomenon of the usual plasma break. The theoretical results are based on the Cerenkov radiation. The peak powers are centred more of less around 5 kHz. At lower latitudes, the results of the theoretical analysis seem to agree to a certain extent with those of experimental findings, whereas the results at higher latitudes show a considerable amount of discrepancy. Moreover, the ground-based results exhibit still further discrepancy that certainly needs further clarification.

IV. CONCLUSION

So far, the hiss observations and the theoretical interpretations of the observations based on the Cerenkov radiation at various latitudes have been presented. It is seen that for a specific range of energetic charged particles, the production of a hiss can be explained through the Cerenkov mechanism and for other values a considerable amount of deviations is dominant. Of course, different mechanisms have also been suggested to explain such phenomena and other types of emissions.

The theoretical interpretations of hiss phenomena on the basis of the Cerenkov mechanism are not so satisfactory at various latitudes, particularly for the lowest frequencies because of their origin at a remote region of the magnetosphere where the obtained parametric values are erroneous. Moreover, most of the theoretical approaches are in connection with the motion of a single particle. Linearized equations have been used in the analysis neglecting the coherent effects among particles within the beam and the collective beam plasma interactions.

The situation may be studied considering the microscopic processes of the emission mechanism and taking into account the effect of coupling. A coherent or a partly coherent emission can be made operative for such phenomena.

The authors are thankful to Prof. M. S. Basu, Director of the Centre of Advanced Study in Radio Physics and Electronics for his encouragement during the progress of the work.

REFERENCES

[1] Eskersley, T. L.: Nature *135* (1935), 104.
[2] Storey, L. R. O.: Phil. Trans. R. Soc. A *246* (1953), 113.
[3] Smith, R. L., Helliwell, R. A.: J. Geophys. Res. *65* (1960), 2583.
[4] Smith, R. L.: J. Geophys. Res. *66* (1961), 3699, 3709.
[5] Helliwell, R. A.: Ann. Geophys. *17* (1961), 76.
[6] Pope, J. H.: J. Geophys. Res. *66* (1961), 67.
[7] Pope, J. H.: J. Geophys. Res. *67* (1962), 412.
[8] Carpenter, D. L.: J. Geophys. Res. *67* (1962), 3345.

[9] Liemohn, H. B., Scraf, L. F.: J. Geophys. Res. *67* ((1962), 1785, 4163.
[10] Liemohn, H. B., Scraf, L. F.: J. Geophys. Res. *69* (1964), 883.
[11] Smith, R. L., Angerami, J. J.: J. Geophys. Res. *73* (1968), 1.
[12] Walter, F., Angerami, J. J.: J. Geophys. Res. *74* (1969), 6352.
[13] Gendrin, R.: *Handbuch der Physik*, Vol. XLIX 3 (Ed.by Flugge, S. and Rawer, K), Springer Heidelberg, 1971, 461.
[14] Gendrin, R.: Spaci Sci. Rev. *18* (1975), 145.
[15] Carpenter, D. L., Stone, K., Siren, J. C., Crystal, T. L.: J. Geophys. Res. *77* (1972), 2819.
[16] Sagredo. J. L., Bullough, K.: Planet and Space Sci. *21* (1973), 913.
[17] Park, C. G.: J. Geophys. Res. *79* (1974), 169.
[18] Karpman, V. I.: Space Sci. Rev. *16* (1974), 361.
[19] Smith, A. j., Smith, I. D., Bullough, K.: J. Atmos. and Terr. Phys. *37* (1975), 1179.
[20] Gurnett, D. A.: *Physics of Solar Planetary Environments*, Vol. II, (Ed. by Williams, D. J.) Ann. Geophys. Un. Washington, D. C. (1976), 760.
[21] Kaiser, T. R., Orr, D., Smith, A. J.: Phil. Trans. R. Soc. B *279* (1977), 225.
[22] Alpert, Y. L., Fligel, D. S.: Planet and Space Sci. *25* (1977), 487.
[23] Park, C. G., Helliwell, R. A.: J. Geophys. Res. *82* (1977), 3634.
[24] Stiles, G. S., Helliwell, R. A.: J. Geophys. Res. *82* (1977), 523.
[25] Alpert, Y. L.: J. Atmos. and Terr. Phys. *42* (1980), 1.
[26] Laaspere, T. W. C., Johnson and Semprebon, L. C.: J. Geophys. Res. *76* (1971), 447.
[27] Gurnett, D. A., Frank, L. A.: J. Geophys. Res. *77* (1972), 172.
[28] Jorgensen, T. S.: J. Geophys. Res. *73* (1968), 1055.
[29] Harang, L., Larsen, R.: J. Atmos. and Terr. Phys. *27* (1965), 481.
[30] Swift, D. W., Srivastava, R. N.: *Final report prepared for Dept. of the Army*, US Army Research Officer, Durham, Contract DAH (O4-69-C-0054), Geophys. Inst., Univ. of Alaska, Fairbanks 1972.
[31] Ellis, G. R. A.: Planet and Space Sci. *1* (1959), 253.
[32] Helliwell, R. A.: *Whistlers and Related Ionospheric Phenomena*. Stanford Univ. Press, Stanford 1965.
[33] Gurnett, D. A.: J. Geophys. Res. *71* (1966), 5599.
[34] Barrington, R. E., Hartz, T. R., Harvey, R. W.: J. Geophys. Res. *76* (1971), 5278.
[35] Mosier, S. R., Gurnett, D. A.: J. Geophys. Res. *77* (1972), 1137.
[36] Jorgensen, T. S.: J. Geophys. Res. *71* (1966), 1367.
[37] Burtis, W. J., Helliwell, R. A.: J. Geophys. Res. *74* (1969), 3002.
[38] Russel, C. T., Holzer, R. E.: *Particles and Fields in the Magnetosphere* (ed. by McCormac, B. M.) D. Riedel Dordrecht 1970, 195.
[39] Heikilla, W. J.: J. Geophys. Res. *76* (1971), 1076.
[40] James, H. G.: J. Geophys. Res. *78* (1973), 4578.
[41] Bullough, K., Hughes, R. W. W., Kaiser, T. R.: *Magnetospheric Physics*, Ed. by McCormac, B. M., (1974), 231.
[42] Ondoh, T., Isozaki, S.: Radio Res. Lab. *15* (1968), 133.
[43] Bullough, K., Denby, M., Gibbons, W., Hughes, A. R. W., Kaiser, T. R., Tatnall, A. R.: Proc. R. Soc. London Ser. A *343* (1975), 207.
[44] Khosa, P. N., Lalmani, R. R., Rausaria, Ahmed, M. M.: Indian J. Radio and Space Phys. *10* (1981), 209.
[45] Twiss, R. O.: Phys. Rev. A *88* (1952), 1392.
[46] Twiss, R. O., Robert, J. A.: Aust. J. Phys. *11* (1958), 424.
[47] Sitenko, A. G., Kolomenskii, A. A.: Sov. Phys. JETP *3* (1956), 410.
[48] McKenzie, J. F.: Proc. Phys. Soc. *87* (1966), 349.

[49] McKenzie, J. F.: Phys. Fluids *10* (1967), 2680.
[50] Eidman, V.: Sov. Phys. JETP *7* (1958), 91.
[51] Eidman, V.: Sov. Phys. JETP *9* (1959), 947.
[52] Ellis, G. R. A.: J. Atmos. and Terr. Phys. *10* (1957), 302.
[53] Mansfield, V. N.: *Radio Phys. Lab.*, Thayer School of Eng., Dartmouth College, Hanover. New Hampshire (1964), 9.
[54] Liemohn, H. B.: Radio Sci. *69* (1965), 741.
[55] Mansfield, V. N.: Astrophys. J. *147* (1967), 672.
[56] Rycroft, M. J.: Radio Sci. *7* (1972), 811.
[57] Taylor, W. W. L., Shawhan, S. D.: J. Geophys. Res. *79* (1974), 105.
[58] Lim, T. L., Laaspere, T.: J. Geophys. Res. *77* (1972), 4145.
[59] Noda, A., Tamao, T.: J. Geophys. Res. *81* (1976), 287.
[60] Kaiser, T. R.: *Earth's Magnetospheric Processes* (Ed. by McCormac B. M.) Reidel Dordrecht (1972), 340.
[61] Singh, B., Mishra, S. N., Tantry, B. A. P.: J. Geomag. Geoelect. *24* (1973), 277.
[62] Singh, B.: J. Geophys. Res. *81* (1976), 2429.
[63] Singh, D. P., Jain, S. K., Singh, B.: Ann. geophys. *34* (1978), 37.
[64] Prakash, R., Singh, D. P., Singh, B.: Planet and Space Sci. *27* (1979), 959.
[65] Iwai, A., Outsu, J., Tanaka, Y.: Proc. Res. Inst. Atmos. Nagoya Univ. *11* (1964), 29.

Received September 11th, 1984