and magnetic records.

The observatories with curves which show more than one maximum are confined to the equatorial zone with the exception of Lz, which as already noted by Mme. Troitskaya at Utrecht shows other peculiar characteristics. In Fig. 13 we present some of these curves in LT. As it is easily seen all these curves present a clear maximum late in the afternoon and this is the predominant one, in many cases there is also a maximum which may be connected with the sunrise (Hn is an exception) and in some cases as in Gh the three maxima appear in the curve.

The existence of the three maxima (or of two) may be due either to the fact that pulsations with different periods are included in the statistics or to a real phenomenon peculiar to the equatorial region. I wish to add that we have only two magnetic observatories reporting *pc*'s in the equatorial zone (PM and Ap). At PM there is a slight indication of the existence of the evening maximum, although the small number of *pc*'s reported makes it rather doubtful and at Ap there is no indication of this maximum; I think this feature of the equatorial stations must be investigated more carefully in the future.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-II, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-1B-P2. Characteristics of Geomagnetic Pulsations

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The classification of geomagnetic micropulsations is discussed, and the question is raised of a revision of the definitions of changes in the geomagnetic field over a much broader spectrum. The paper then gives an account of the research, both observational and theoretical, at present being carried out in the field of micropulsations at the Institute of Earth Sciences, University of British Columbia.

§1. Introduction

I would like to begin on a philosophical note and to ask in all seriousness why are we interested in rapid variations in the Earth's electric and magnetic fields and whether or not the same information cannot be obtained more easily from other upper atmospheric phenomena? There are a host of such phenomena (such as visual and radar aurora, airglow, whistlers, solar flares, cosmic rays, ionospheric disturbances) which may be lumped together under the title " solar terrestrial relationships ", and it is not surprising that correlations should exist between many of these events. In many instances we may be observing different manifestations of what was originally some solar disturbance, but it is not easy to distinguish between what is fundamental phenomenon and what may turn out to be relatively unimportant side issues. Of course, if for example an increase in activity in a certain sub-audio frequency band is found to be a precursor of geomagnetic storms as Maple has suggested, then such a result would be of fundamental importance. But it must not be forgotten that whereas in the laboratory, experiments can be carefully planned and executed with a view to settling definite questions, Nature, on the other hand, is continually making a multitude of " experiments " simultaneously all over the Earth. It is not easy to disentangle all these experiments and to sort out cause and effect—this may require long periods of observation from many stations well distributed over the

Earth. With Nature working 24 hours a day, seven days a week, 52 weeks a year, it is difficult to take a representative sample of her work—especially when diurnal, seasonal and annual trends are to be looked for. As interest extends to higher and higher frequencies, even the storage of the rolls of paper and tape becomes a problem. The proper collection and analysis of data is, I believe, the major problem in this field, and one that if done poorly can lead to erroneous results. Some time ago I tried to collect together all the results that had been obtained on micropulsations. While most investigators agreed on certain general trends, I found many, many cases of contrary findings. These may have been due to a variety of causes, such as different equipment with different sensitivities or different samples and methods of analysis. Often data collected for a year or more tended to contradict data collected for only a month or so. To give but one example, in a recent paper, Ellis (1960)[1] analysed the records obtained over three months from three stations at approximately the same geomagnetic longitude but with geomagnetic latitudes of 29°S, 43°S and 52°S. He found no observable change in the period of micropulsations with latitude. Using the same data Duncan (1961)[2] found a latitude dependence, the median mid-day period being 19, 23 and 27 seconds.

I would also like to discourage the wholesale and aimless collection of data. In spite of the advantage of running an observatory to preserve a continuous record of events, I would prefer to try and design an experiment which would answer one specific problem. This may well require the simultaneous observations of certain field quantities for some time, but when the experiment was over, observations should cease until the next problem is formulated—and this may well require an analysis of the results of the previous experiment.

Recently Troitskaya (1961)[3] made a rather radical suggestion that the existing definitions of *Pc*'s, *Pt*'s, etc., were artificial and that pulsations should rather be classified according to their association with other physical phenomena. In other words, instead of defining fluctuations by their period, amplitude, duration or frequency and time of occurrence, it would be more logical to identify them by their association with aurora, magnetic storms, cosmic ray outbursts or other upper atmospheric phenomena. I think that this is an excellent suggestion although it might not be too easy to put into practice. Thus in discussing pulsations in the period range 1–15 seconds, she classifies

SIP (Short irregular pulsations mainly of 6–15 second period) They are a microstructure of other macroscopic forms of disturbance of the Earth's magnetic field, and show an extremely high correlation with aurora in polar regions.

PP (Pearls, 1–4 second period). These usually occur on magnetically quiet days and, unlike *SIP*, do not represent a microstructure of some characteristic form of disturbance of the Earth's magnetic field. They often appear to be excited when there is a sharp increase in cosmic ray intensity in the stratosphere.

IPDP (intervals of pulsations diminishing on periods). These occur as a rule during the main phase of a magnetic storm and coincide with a number of other upper atmospheric disturbances such as a sharp fall of *foF*2, propagation of red aurora in low latitudes, bursts of X-rays in the stratosphere, sharp increase of cosmic noise absorption.

It is interesting to note that Benioff (1960)[4] in a recent paper on geomagnetic fluctuations in the period range 0.3–120 seconds divided them into 4 groups each with its own particular association with other phenomena. Until we know more about the cause of micropulsations and their relationship to other upper atmospheric phenomena some more formal classification is necessary, but it is very important that restrictions are not imposed by too rigid definitions. Strict adherence to a narrow classifiication can but hamper further progress in this field. I would like to suggest that the whole spectrum of the electromagnetic field be looked at again from this point of view. Nishida and myself (1961)[5] have been studying world wide simultaneous changes in the geomagnetic field which take place frequently and which are not necessarily *ssc* or *si*. We have found certain deeper characteristics: the relation between micropulsations and these changes particularly at an *ssc* is extremely important.

There are two scales on which one can study geophysical phenomena—regional and global. Thus, on the one hand, a geologist may map and study in great detail a very small area of the Earth, while on the other a geophysicist may view the area as part of a very much larger tectonic feature. Such a division applies equally well to a study of rapid variations in the Earth's electric and magnetic fields—both local and world wide effects must be studied. In this paper I will describe some of the work which we are carrying out at the Institute of Earth Sciences at the University of British Columbia. These include both experimental and theoretical studies. I will discuss first the observational work which we have carried out in cooperation with other laboratories and confine myself to three projects.

§ 2. Observational Studies

(1) In the course of a program designed to assess the distribution and characteristics of geomagnetic micropulsations a series of two-station operations was conducted by the Pacific Naval Laboratory in 1958 and 1959. These showed that each field station, when compared with the base station at Victoria, differed significantly in the partition of signal strength among its conventional orthogonal components. Of the several sites on which measurements were made the two which showed the greatest difference were Victoria, British Columbia, and Ralston, Alberta. The topography and presumably also the conductivity structure showed greater differences for this pair of stations than for any other pair, the former site being on a rocky seashore in a mountainous region and the latter being on the Great Plains.

Curves A and E of Fig. 1 show how both the magnitude of the ratios of the vertical to the horizontal components and their frequency dependence differ. Curve D shows the intermediate characteristics of Summerland, British Columbia, a site far from the sea but in the midst of rugged terrain. The evidence suggests that low values of the Z/H ratio are associated with regions of uniform conductivity while high values are associated with conductivity gradients or discontinuities. The signal partition in Victoria, situated on

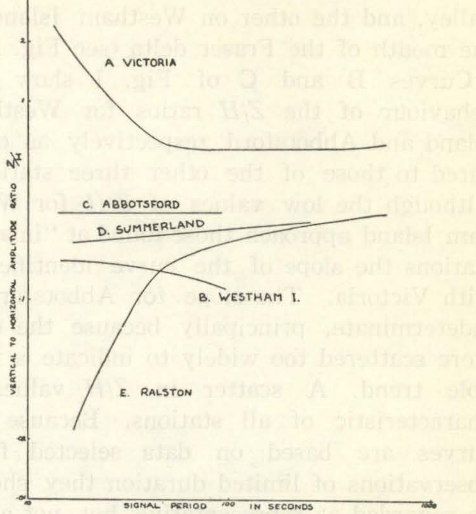

Fig. 1. Z/H ratio as a function of period for different stations.

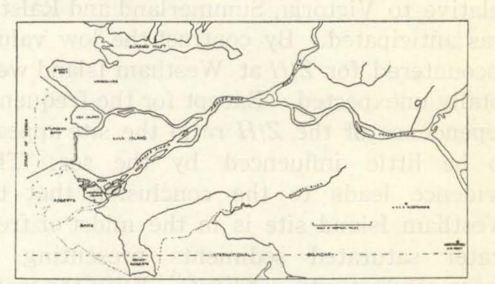

Fig. 2. Map of the Fraser Delta showing the position of the stations at Westham Island and Abbotsford.

an abrupt rock-sea interface is thus regarded as atypical.

An experiment to determine the effect of the proximity of the sea on the Z/H ratio was undertaken during the summer of 1960. This called for a sharply defined seawater-land interface of simple, known configuration in a region free of topographic features. No such ideal site was accessible but the delta and lower valley of the Fraser River were considered to approach the requirements of a model which would yield useful data. The delta sediments are known to be about a mile deep and their seaward face, except for the river channels, is relatively uniform in section. However, the extent and configuration of salt intrusion in the sediments are not known. Mountains generally line the valley but are several miles from the seaward face. Two stations were occupied, one at Abbotsford about 30 miles inland up the valley, and the other on Westham Island at the mouth of the Fraser delta (see Fig. 2).

Curves B and C of Fig. 1 show the behaviour of the Z/H ratios for Westham Island and Abbotsford respectively as compared to those of the other three stations. Although the low values of Z/H for Westham Island approach those found at "inland" stations the slope of the curve identifies it with Victoria. The slope for Abbotsford is indeterminate, principally because the data were scattered too widely to indicate a reliable trend. A scatter in Z/H values is characteristic of all stations. Because the curves are based on data selected from observations of limited duration they should be regarded as representative but not absolute.

The intermediate behaviour of Abbotsford relative to Victoria, Summerland and Ralston was anticipated. By contrast the low values encountered for Z/H at Westham Island were totally unexpected. Except for the frequency dependence of the Z/H ratio the site appears to be little influenced by the sea. This evidence leads to the conclusion that the Westham Island site is in the midst of fresh water saturated sediments presenting no sharp conductivity gradients. Even the water which at high tide floods over the bank to within a few yards of the detector array is normally fresh for perhaps two miles to seaward and contributes little to a conductivity gradient. Where seawater intrudes into the floodwater or sediments it tends to avoid the surface so that its form is that of a tongue or wedge, limited to a very few feet in depth in the river channels or over the banks. Thus restricted in cross-sectional area and in its proximity of approach it has little effect on the overall conductivity. On the other hand the deeper sea some five miles away must present a conductivity discontinuity even if the interface between salt and fresh water in the sediments is diffuse. At this distance the effect of such a discontinuity is apparently small, *i.e.* the effect of the proximity of the sea on the Z/H ratio is of secondary importance within a distance of five miles or less.

(2) The second experiment was also carried out last summer when simultaneous measurements of the Earth's magnetic field were made by the Pacific Naval Laboratory and the Universities of British Columbia, Alberta and Texas. Our station was at Abbotsford 30 miles inland from the Pacific coast, the Pacific Naval Laboratory occupied a site at Suffield in the plains of Alberta some 470 miles from the coast, the University of Texas operated at Austin in flat lying country some 150 miles from the Gulf of Mexico, whilst the University of Alberta ran a mobile station occupying a number of different sites. I will not attempt to describe all the results of this combined operation, which included the compilation of an atlas of typical events as recorded at all four stations and an analysis of a number of energy spectra, but will confine myself to the observations of pearls.

Oscillations of nearly sinusoidal shape and with periods ranging from about 0.3 to 3 seconds have been called "pearls" by Troitskaya (1957)[6]. The wave trains usually exhibit beat—the envelope of a sequence of oscillations resembling a necklace of oval pearls. The pulsations may occur as separate bursts lasting 1–2 minutes and as continuous series of pulsations lasting several tens of minutes. The appearance of pearls is not very common —Benioff (1960)[4] has observed that in Southern California the number of occurrences is of the order of 30 a year. This number is probably representative of middle latitudes, although it may be increased by a factor of two or three in the polar regions (Troitskaya, 1959)[7]. The comparative rarity of pearls would indicate that the ionosphere is an opaque shield for waves of this frequency most of the time. It is also possible that pearls are more frequent but that their amplitude is below the threshold of the detecting equipment.

During the period of operations, pearls were only recorded on one occasion when they were observed at Suffield and Abbotsford, but not at Austin. Fig. 3 reproduces part of the Abbotsford record, the two lower curves showing pearls in their pure form, the longer period pulsations which were also present having been filtered out. The onset of pearls at Abbotsford and Suffield was not simultaneous but occurred at Suffield 38 minutes earlier. Records were obtained from

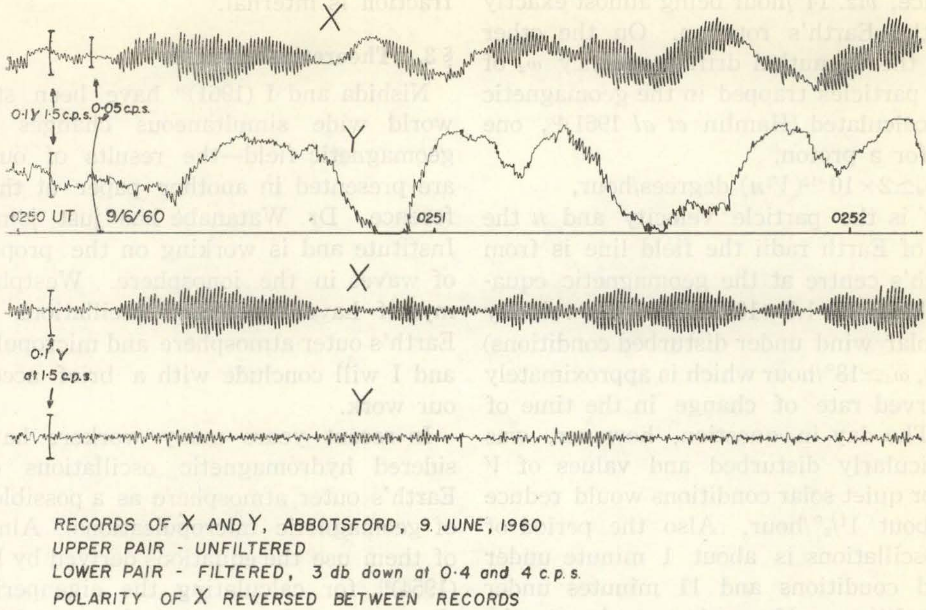

Fig. 3. Records of X and Y, Abbotsford, 9th June, 1960. Upper pair unfiltered, lower pair filtered.

Benioff for Uppsala, Reykjavik, Ruth, Isabella and Huancayo. It appears that pearls on this occasion were observed progressively earlier at eastern stations. Figs. 4 and 5 show a plot of the time of occurrence of pearl activity against geographic and geomagnetic longitude respectively. The graphs are practically linear and show that the onset of these pulsations moved westward at an approximate rate of 14°/hour (geographic) and 19°/hour (geomagnetic).

Troitskaya (1959)[7] has shown that the diurnal distribution of pearls is different for middle latitude and polar stations. At middle latitudes pearls are recorded mainly during the evening, night and early morning hours, whereas in the polar regions they may occur at any time. This general tendency has also been found by Benioff (1960)[4]. Troitskaya (1959)[7] also observed that pearls were often recorded simultaneously over a wide range of both latitude and longitude—particularly on disturbed days. There appears to be both a G.M.T. and an L.M.T. control—the L.M.T. control being weakened on highly disturbed days.

One explanation of Figs. 4 and 5 is that this onset of pearls is entirely L.M.T. dependent—the rate of change of onset of

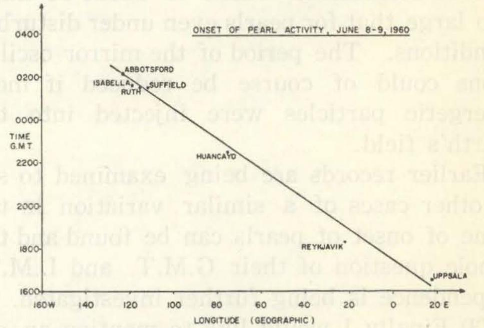

Fig. 4. Time of onset of pearl activity, June 8-9th, 1960, as a function of geographic longitude.

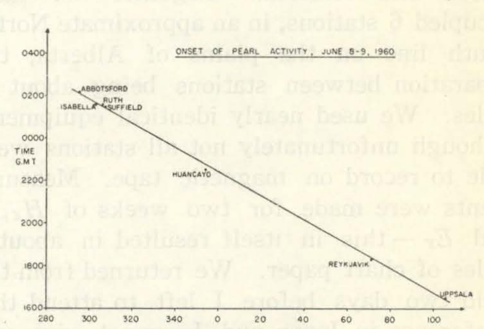

Fig. 5. Time of onset of pearl activity, June 8-9th, 1960, as a function of geomagnetic longitude.

occurrence, *viz*. 14°/hour being almost exactly that of the Earth's rotation. On the other hand, if the azimuthal drift frequency ω_d of charged particles trapped in the geomagnetic field is calculated (Hamlin *et al* 1961)[8], one obtains for a proton,

$$\omega_d \simeq 2\times10^{-12}(V^2n) \text{ degrees/hour,}$$

where V is the particle velocity and n the number of Earth radii the field line is from the Earth's centre at the geomagnetic equator. Taking $V=1.5\times10^6$ m/sec (the volocity of the solar wind under disturbed conditions) and $n=4$, $\omega_d \simeq 18°$/hour which is approximately the observed rate of change in the time of onset. The day in question, however, was not particularly disturbed and values of V and n for quiet solar conditions would reduce ω_d to about $1^1/_2$°/hour. Also the period of mirror oscillations is about 1 minute under disturbed conditions and 11 minutes under quiet conditions. If pearls are due to the drift of protons trapped in the Earth's magnetic field, one would expect to observe the phenomenon with the frequency of the mirror oscillations which is about 50 times too large that for pearls even under disturbed conditions. The period of the mirror oscillations could of course be reduced if more energetic particles were injected into the Earth's field.

Earlier records are being examined to see if other cases of a similar variation in the time of onset of pearls can be found and the whole question of their G.M.T. and L.M.T. dependence is being further investigated.

(3) Finally I would like to mention an experiment that we have carried out this summer in cooperation with the Universities of California and Alberta. Together we have occupied 6 stations, in an approximate North-South line on the plains of Alberta, the separation between stations being about 70 miles. We used nearly identical equipment, although unfortunately not all stations were able to record on magnetic tape. Measurements were made for two weeks of H_X, Z and E_Y — this in itself resulted in about 2 miles of chart paper. We returned from the field two days before I left to attend this conference in Japan and I cannot give you any details of the analyses. Amongst other things, we hope to decide what fraction of the signal is of external origin and what fraction is internal.

§ 3. Theoretical Studies

Nishida and I (1961)[5] have been studying world wide simultaneous changes in the geomagnetic field—the results of our work are presented in another paper at this conference. Dr. Watanabe has just joined our Institute and is working on the propagation of waves in the ionosphere. Westphal and myself have considered oscillations of the Earth's outer atmosphere and micropulsations and I will conclude with a brief account of our work.

In recent years many workers have considered hydromagnetic oscillations of the Earth's outer atmosphere as a possible cause of geomagnetic micropulsations. Almost all of them use the equations derived by Dungey (1954)[9] for calculating the eigenperiods of the system. Because of the complexity of the equations the coupling terms, which in spherical polar coordinates contain $\partial/\partial\phi$ are usually neglected. For this reason the equations of small hydromagnetic oscillations have been derived in cylindrical coordinates with the main magnetic field lying in the plane perpendicular to the axis of the cylinder.

Since the structure of the equations in this system is somewhat simpler than in spherical polar coordinates, it has been possible to obtain the eigenperiods of toroidal oscillations as a function of co-latitude without making any approximations. Using an electronic computer it was possible to extend the calculations to the case of a non-uniform plasma density distribution, as used by Dessler (1958)[10] in his studies on the geomagnetic field.

In the past most workers have assumed the Earth's field to be a geocentric dipole. As a result of recent studies, however, it appears that the geomagnetic field does not extend as far into outer space as was assumed but that to a first approximation it is confined to a cavity (Dungy, 1954[9]; Parker, 1958[11]). For this reason the equation of toroidal oscillations has been applied to a compressed dipole field.

For a constant plasma density distribution in a normal dipole field the eigenperiods of toroidal oscillations are shown in Fig. 6.

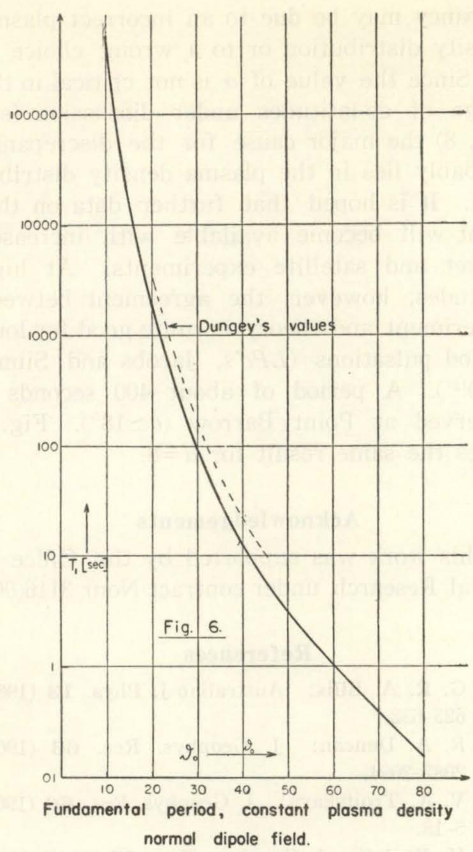

Fig. 6. Fundamental period of oscillating lines of force as a function of co-latitude. Constant plasma density, normal dipole field.

It can be seen that they range from very large values down to zero as the co-latitude θ varies from 0° to 90°. This property is a direct result of the fact that the length of the lines of force vary from infinity to zero. For comparison the eigenperiods of toroidal oscillations as obtained by Dungey are also shown in Fig. 6. The agreement is very good and illustrates the legitimacy of the simplified representation.

Since the assumption of a constant plasma density distribution above the Earth's surface is probably not correct, the eigenperiods of the toroidal equation were calculated using a variable plasma density distribution. As shown in Fig. 7, the values coincide with those obtained for a constant plasma density at low co-latitudes but differ very much at high co-latitudes. This is due to the passage of the lines of force through regions of higher plasma density which counteracts the

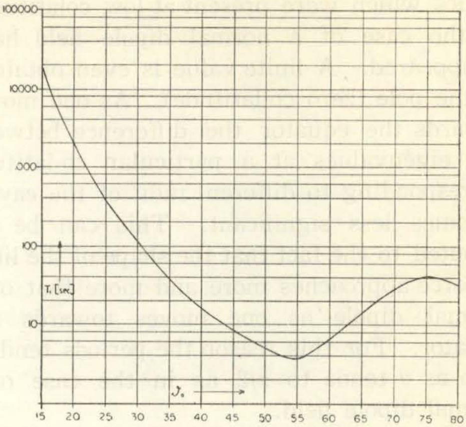

Fig. 7. Fundamental period of oscillating lines of force as a function of co-latitude. Variable plasma density, normal dipole field.

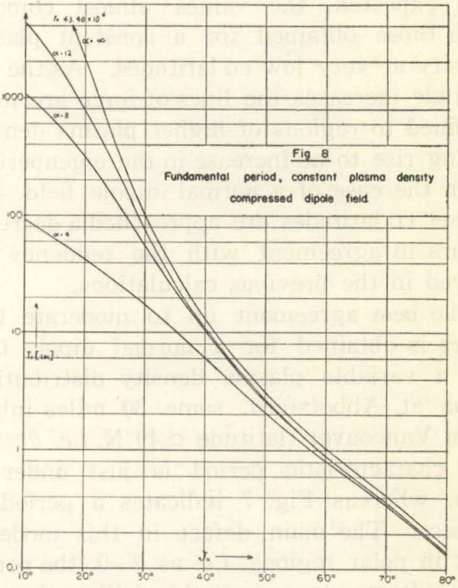

Fig. 8. Fundamental period of oscillating lines of force as a function of co-latitude. Constant plasma density, compressed dipole field. α is the radius of the cavity in which the Earth's dipole field is confined, expressed in units of the Earth's radius.

shortening of the lines of force.

The next step in improving the existing theory was to modify the dipole field by confining it to a first approximation in a cavity α Earth radii in extent. Substituting the modified dipole field into the toroidal equation the eigenperiods were computed using a constant plasma density distribution. From Fig. 8 one can see that the large values which were present at low colatitudes in the case of a normal dipole field have disappeared. A finite value is even obtained at the pole (zero co-latitude). As one moves towards the equator the difference between the eigenvalues at a particular co-latitude corresponding to different radii of the cavity becomes less significant. This can be attributed to the fact that the shape of the lines of force approaches more and more that of a normal dipole as one moves towards the equator. For this reason the periods tend to zero as θ tends to $\pi/2$ as in the case of a normal dipole field.

Finally, using the modified dipole field in the equation of toroidal oscillations, the eigenvalues were computed in the case of a variable plasma density distribution. As was expected, the values almost coincide with those obtained for a constant plasma density at very low co-latitudes. As the co-latitude increases the lines of force are more confined to regions of higher plasma density giving rise to an increase in the eigenperiods as in the case of a normal dipole field. As higher co-latitades are approached a decrease occurs in agreement with the tendency observed in the previous calculations.

The best agreement up to moderate latitudes is obtained for a normal dipole field and a variable plasma density distribution. Thus at Abbotsford, some 30 miles inland from Vancouver (latitude $\simeq$49°N, *i.e.* $\theta\simeq 41°$) the characteristic period is just under 20 secs, whereas Fig. 7 indicates a period of 18 secs. The main defect in this model is that in polar regions, *i.e.* as $\theta \to 0$, the period $\to\infty$. It was to correct this failing that the model of a compressed dipole field was introduced.

Unfortunately, the agreement between the observed and calculated values is not too satisfactory for this model in middle and low latitudes. Apart from the fact that the model may not be appropriate, the discrepancy may be due to an incorrect plasma density distribution or to a wrong choice of α. Since the value of α is not critical in the range of co-latitudes under discussion (see Fig. 8) the major cause for the discrepancy probably lies in the plasma density distribution. It is hoped that further data on this point will become available with increased rocket and satellite experiments. At high latitudes, however, the agreement between experiment and theory is quite good for long period pulsations (*LPc*'s, Jacobs and Sinno, 1960[12]). A period of about 400 seconds is observed at Point Barrow ($\theta\simeq 18°$). Fig. 8 gives the same result for $\alpha=8$.

Acknowledgements

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Discussion

Troitskaya, V. A.: As regards pulsations of the pearl type we get clear evidence, that the frequency of their occurrence increases with diminishing of solar activity.

Vestine, E. H.: In view of differences noted in pulsations at stations differing in geology, would you advocate ocean stations, say over the Pacific area, for making careful observations of pulsations?

Jacobs, J. A.: Yes, although oceanic islands with a sharp sea-land interface would not be a good subsitute for an inland station with known regular geology.

Campbell, W. H.: This question concerns your discussion of the Victoria-Ralston experiment which you report as having been carried out to indicate the effect of the ocean on the direction of the pulsation fields. You, of course, realize that the east station was closer to the auroral zone. It seems that such proximity would affect your conclusions. Why was it not considered?

Jacobs, J. A.: The 3 stations, Vectoria, Westham Island, and Abbotsford are all close together and here approximately the same geomagnetic latitude. My main results concern differences between these three. Ralston is, as you remark, closer to the auroral zone and this would affect results from that station.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-1B-P3. Fine Structure of Magnetic Storms in Respect of Micropulsations ($T<20$ sec)*

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The investigations of magnetic storms allowed to obtain many interesting conclusions concerning both the peculiarities of the development of this most violent disturbance of the Earth's field and many important questions such as the structure of the high atmosphere, development of the ring-current, the scale of the C-F cavity, *etc.*[1)-6)]. Most of these investigations were carried out using standard magnetic records. Only during the last decade due to the wide growth of interest to pulsations in the magnetic field and Earth currents began the observations with greater time scale and sensitivity[7)-14)]. It was realized that in these rapid variations are mirrored different fine processes which take place at the border of the C-F cavity, as well as in the whole body of the high atmosphere including the ionosphere[7)-14)].

Therefore it is of undoubted interest to use the pulsations records in the analysis of the microstructure of magnetic storms. As the first results show this analysis reveals many new features of magnetic storms development. The new facts may and have to be used in the theory of magnetic storms, and in discussions of other problems such as the structure of solar corpuscular streams, trapping of the charged particles by the magnetic field and in the course of investigations of different geophysical phenomena in the high atmosphere.

Experimental Data

The results given below were mainly obtained in the course of processing of ultra-quick run earth-current records at stations located in the Arctic, the Antarctic and in the middle latitudes of the Northern hemisphere ($\lambda \sim 120°$)[15)]. The records were conducted 24 hours running, with time scale 1/2 mm in a second. Pulsations with periods from fractions of a second (which can be still recognized on the records) to 15-20 seconds were analyzed. The frequency response of the installations did not allow to record pulsations with greater periods and the latter

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* The paper entitled "The Connection of *pc* and and *pt* Pulsations with Magnetic Storms", presented by V.A. Troitskaya, I.I. Rokityansky, K.Yu. Zibin, R.V. Schepetnov and D. A. Rokityanskaya, is read partially by Troitskaya as a part of this paper.