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Commission 4. Magnetospheric Radio

1. Constitution of the Atmosphere at Magnetospheric Levels

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1. Composition

Prior to 1961 it was generally accepted that the main constituent of the atmosphere above 300 km was atomic oxygen up to an altitude of about 1000 km and that at higher altitudes hydrogen would predominate. Direct experimental evidence for the presence of neutral hydrogen in the outer atmosphere has come from the high resolution Lyman α spectrum obtained by Purcell and Tousey [1960]. From the absorption core of their Lyman α spectrum, the total content of hydrogen above the altitude of the rocket measurement has been determined. Johnson [1961] has interpreted this hydrogen content to be distributed in the form of a "geocorona." The problem of interpretation of the Lyman α observations in terms of hydrogen and its location with respect to the earth has recently been reviewed in detail by Donahue [1962]. The computation of the distribution of neutral hydrogen is complicated by the fact that at magnetospheric levels "exospheric" conditions prevail, i.e., the mean free path of neutral hydrogen is greater than the local scale height. Because of the escape of particles with high velocities, the velocity distribution is, strictly speaking, non-Maxwellian and the distribution of density with height does not follow the simple hydrostatic equation, but has to be computed by taking into account ballistic escape, ballistic reentry and bound-orbiting particles. Such computations have been made by Öpik and Singer [1961] and by Johnson [1961]. Out to a geocentric distance of about two earth radii, a simple hydrostatic distribution, however, still represents a reasonably good approximation.

Photoionization and/or charge exchange with oxygen ions of the neutral hydrogen of the geocorona lead to the protons constituting the "protonosphere." The ions at magnetospheric levels are distributed according to a diffusive equilibrium distribution, i.e., hydrostatically supported but constrained by the earth's magnetic field. For ions the mean free path is short enough so that the concept of an ion-exosphere is not applicable [Johnson, 1962]. While the diffusive equilibrium distribution of an ionic species was generally considered to be governed by a scale height twice that of the corresponding neutral species, it was pointed out by Mange [1960, 1961] that this concept is not justified for a minor ion in the presence of other ions. The electric field, which is set up to prevent further charge separation of electrons and ions diffusing under gravity, and which is proportional to the mean mass of the (singly charged) positive ions, causes the density of minor light ions first to *increase* with altitude until it becomes predominant, after which it shows the usual exponential decrease with altitude according to a scale height approaching twice that of the corresponding neutral constituent. Subsequently to Mange's independent derivation of the equation governing the distribution of singly charged ions in the presence of other singly charged ions, it was realized that the same problem had been solved before by Dungey [1955], and originally as long as four decades ago [Pannekoek, 1922; Eddington, 1926]. The distribution of protons in the protonosphere according to this concept, and their relation and coupling to the ionospheric F-region where oxygen ions predominate, have been discussed in great detail by Hanson and Ortenburger [1961].

In 1961, Nicolet [1961] suggested that neutral and ionized helium should be an important constituent in the upper atmosphere. He pointed out that the presence of neutral helium would provide a sensible solution to the problem of high atmospheric densities at 1600 km deduced from the drag of the Echo I balloon satellite. The first experimental evidence, from charged particle observations, for the importance of helium in the upper atmosphere was presented before a session of U.S. Commission 4 at the Fall-URSI-Meeting in Austin, Texas, 1961 [Hanson, 1962; Bourdeau, Whipple, Donley, and Bauer, 1962]. Hanson [1962] inferred the presence of helium ions from an ion density profile obtained by Hale (1961) with a Scout rocket. Hanson concluded from the analysis of this data that the concentration of He^+ was in agreement with Nicolet's estimates and that the layer where He^+ was predominant extended over about 2000 km, from 1200 to 3400 km, at a time when the atmospheric temperature corresponded to 1600° K. He also suggested that He^+ is lost by an ion-atom interchange process involving molecular nitrogen, and that no large diurnal change in the helium ion concentration should occur. More recently Bates and Patterson [1962] have shown that the loss process for He^+ with N_2 is not possible, but that the one involving O_2 seems to be responsible for the loss of He^+.

The first direct experimental evidence for the presence of He^+ was provided by the ion retarding potential measurement on Explorer VIII [Bourdeau, Whipple, Donley, and Bauer, 1962]. This measurement showed a ratio of $He^+/O^+=1.3\pm0.3$ at an altitude of 1630 km, where the simultaneously measured electron temperature was 1750 ± 200 °K. Additional evidence for a transition from O^+ to He^+, rather than directly to H^+, has come from a rocket measurement of the electron density distribution [Bauer and Jackson, 1962]. The presence of He^+ and H^+ in the upper atmosphere has now also been identified directly with an RF ion spectrometer [Taylor, Brinton, and Smith, 1962]. More recently ion composition measurements on the Ariel satellite have also shown the presence of He^+ as well as a significant diurnal variation of the altitude range where He^+ is the predominant ion [Willmore, Boyd, and Bowen, 1962]. These data, as well as a recent nighttime ion density profile obtained with a Scout rocket [Donley, 1963], indicate that at low atmospheric temperatures the layer where He^+ is predominant is only a few hundred km thick compared to a thickness of 2000 km at 1600°K determined by Hanson, with correspondingly lower altitudes of transitions from O^+ to He^+ and He^+ to H^+. Such a strong variation with temperature in the thickness of the helium ion layer is in accordance with a suggestion by Bauer [1963].

The possible presence of doubly charged oxygen ions (O^{++}) in the upper ionosphere has been suggested by Nakada and Singer [1962] on the basis of the abundance of O^+ and an adequate photoionization rate for their formation. In this connection they have investigated the distribution of multiply charged ions in an ion mixture, for which no analytical expression of the kind derived by Mange [1960] exists, and have shown by numerical integration that the concentration of O^{++} would also increase with altitude relative to O^+ and may, depending on loss rates, become an important ionic constituent. The presence of O^{++}, however, has not yet been verified experimentally.

2. Temperature

The kinetic gas temperature of the atmosphere at magnetospheric levels has been determined from satellite drag observations assuming model distributions of the mean molecular weight. Above 300 km this temperature should be independent of altitude because of the high thermal conductivity. The kinetic gas temperature in this isothermal region has been found to vary with the solar cycle and to show short-term fluctuations which are correlated with the 10.7 cm radiation from the sun, as well as with geomagnetic activity [Jacchia, 1961; Priester, 1961; Harris and Priester, 1962]. A diurnal variation having a minimum at 4 a.m. local time and a maximum at about 2 p.m. is indicated from the satellite data.

While the kinetic gas temperature in the upper atmosphere has only been inferred from satellite drag measurements, direct measurements of the electron and ion temperatures have been made with the help of space vehicles. The vertical profiles of electron temperature up to about 400 km have been measured by means of the Langmuir probe technique [Spencer, Brace, and Carignan, 1962; Brace, 1962]. These measurements indicate that at midlatitudes for quiet ionospheric conditions, the daytime electron temperature attains a maximum at about 230 km, approaching an isothermal behavior at altitudes above 300 km.

This measurement is in good agreement with theoretical investigations [Hanson and Johnson, 1961; Hanson, 1962; Dalgarno, McElroy, and Moffett, 1962] which show that, for solar ultraviolet as the major heat source, the only departure from temperature equilibrium would occur in the region between 200 and 400 km altitude. At higher altitudes, the daytime electron temperature and the ion (and gas) temperature are expected to be equal, at least under quiet conditions. A nighttime measurement of electron temperature shows perfect isothermal behavior throughout this altitude range [Brace, 1962]. Departures from thermal equilibrium extending throughout the ionospheric *F*-region have been reported for disturbed ionospheric conditions at middle latitude and appear to be the rule in auroral regions [Spencer, Brace, and Carignan, 1962]. The gas temperature in the upper ionosphere has also been determined from the exponential decrement of electron and ion density profiles. These measurements show evidence of an isothermal behavior, since the scale height of the electron-ion gas is constant within a few percent over an altitude range of a few hundred kilometers. Temperatures derived from these scale heights, assuming thermal equilibrium, have been found to be in good agreement with kinetic gas temperatures expected from the correlation with solar 10.7 cm flux, thus providing indirect evidence for temperature equilibrium [Bauer and Bourdeau, 1962]. Direct measurements of electron temperature at magnetospheric levels have been made by means of Langmuir probes on the Explorer VIII satellite [Serbu, Bourdeau, and Donley, 1961]. These measurements also show, within their error-limits, agreement with model values of kinetic gas temperatures, except during the sunrise period when high electron temperatures seem to be prevalent. More recently, similar measurements have been made on the Ariel satellite [Willmore, Boyd, and Bowen, 1962] in the altitude region between 400 and 1200 km which indicate a latitude dependence, with midday values of 1200 °K at the equator and 1600 °K at a latitude of 55 °N. Preliminary topside sounder satellite results are in qualitative agreement with such a latitude dependence [Knecht and Van Zandt, 1963]. The Ariel measurements also show high electron temperatures during the sunrise period while at other times the electron temperatures are equivalent to the simultaneously determined ion temperatures.

Ion temperatures and the departure from thermal equilibrium in the upper ionosphere have also been determined by ground-based magnetospheric sounders using the incoherent backscatter technique. Evans [1962] has reported measurements for a few days covering an altitude range up to 800 km, which show temperature equilibrium ($T_e=T_i$) during the night as expected, but a positive temperature gradient, and during the day departures from equilibrium in the entire region above 200 km. The latter can be interpreted either as a constant ratio T_e/T_i, with T_e and T_i showing a height gradient, or as a variable ratio T_e/T_i, with T_i=constant and an even stronger height-dependence of T_e. The time of maximum departure from equilibrium according to his data is at noon, reaching a value of $T_e/T_i=1.6$. This is in disagreement with satellite measurements which show high electron temperatures only during the sunrise period, as well as with incoherent backscatter measurements by Bowles, Ochs, and Green [1962], who also found the times of departure from thermal equilibrium to be only during the sunrise period and during disturbed ionospheric conditions. The present discrepancies between space-flight measurements of charged particle temperatures and those determined by means of the incoherent backscatter technique obviously need to be resolved. It should be understood, however, that generalizations concerning the thermal properties of the upper atmosphere based as yet upon only a small number of observations may be premature.

References

Bates, D. R., and T. N. L. Patterson (1962), Helium ions in the upper atmosphere, Planet. Space Sci. **9**, 599–605.

Bauer, S. J. (1963), Helium ion belt in the upper atmosphere, Nature **197**, 36–37.

Bauer, S. J., and R. E. Bourdeau (1962), Upper atmosphere temperatures derived from charged particle observations, J. Atmos. Sci. **19**, 218–225.

Bauer, S. J., and J. E. Jackson (1962), Rocket measurement of the electron density distribution in the topside ionosphere, J. Geophys. Res. **67**, 1675–1677.

Bourdeau, R. E., E. C. Whipple, J. L. Donley, and S. J. Bauer (1962), Experimental evidence for the presence of helium ions based on Explorer VIII satellite data, J. Geophys. Res. **67**, 467–475.

Bowles, K. L., G. R. Ochs, and J. L. Green (1962), On the absolute intensity of incoherent scatter echoes from the ionosphere, J. Res. NBS **66D** (Radio Prop.), 395–407.

Brace, L. H. (1962), The dumbell electrostatic ionosphere probe: ionosphere data, Univ. of Michigan Sci. Rept. JS–3, 139 pp.

Dalgarno, A., M. B. McElroy, and R. J. Moffett (1962), Electron temperatures in the ionosphere, Geophysics Corp. of Amer, Tech. Rept. 62–11–N, 55 pp.

Donahue, T. M. (1962), Excitation of the Lyman α in the night sky, Space Sci. Rev. **1**, 135–153.

Donley, J. L. (1963), Experimental evidence for a low ion transition altitude in the upper nighttime ionosphere, J. Geophys. Res. **68**.

Dungey, J. W. (1955), The electrodynamics of the outer atmosphere, The Physics of The Ionosphere (Phys. Soc., London).

Eddington, A. S. (1926), The Internal Constitution of the Stars, 272–274 (Cambridge Univ. Press).

Evans, J. F. (1962), Diurnal temperature variation of the *F*-region, J. Geophys. Res. **67**, 4914–4920.

Hale, L. C. (1961), Ionospheric measurements with a multigrid potential analyzer, J. Geophys. Res. **66**, 1554.

Hanson, W. B. (1962a), Upper atmosphere helium ions, J. Geophys. Res. **67**, 183–188.

Hanson, W. B. (1962b), Electron temperatures in the upper atmosphere, Third International Space Science Symposium of COSPAR, Washington, D.C.

Hanson, W. B., and F. S. Johnson (1961), Electron temperatures in the ionosphere, Memoires Soc. Roy. Sci. Liege, Tome **IV**, 390–423.

Hanson, W. B., and I. B. Ortenburger (1961), The coupling between the protonosphere and the normal *F* region, J. Geophys. Res. **66**, 1425–1455.

Harris, I., and W. Priester (1962), Theoretical models for the solar cycle variation of the upper atmosphere, J. Geophys. Res. **67**, 4585–4591.

Jacchia, L. G. (1961), A working model for the upper atmosphere, Nature **192**, 1147.

Johnson, F. S. (1961), The distribution of hydrogen in the telluric hydrogen geocorona, Astrophys. J. **133**, 701.

Johnson, F. S. (1962), Physics of the distribution of ionized particles in the exosphere, Electron Density Profiles in the Ionosphere and Exosphere, ed. B. Maehlum 404–413 (Pergamon Press, New York and London).

Knecht, R. W., and T. E. Van Zandt (1963), Some early results from the ionosphere topside sounder satellite, Nature **197** (in press).

Mange, P. (1960), The distribution of minor ions in electrostatic equilibrium in the high atmosphere, J. Geophys. Res. **65**, 3833–3834.

Mange, P. (1961), Diffusion in the thermosphere, Ann. Geophys. **17**, 277–291.

Nakada, M. P., and S. F. Singer (1962), Multiply ionized oxygen in the magnetosphere, URSI-Spring Meeting, Washington, D.C.

Nicolet, M. (1961), Helium, an important constituent in the lower exosphere, J. Geophys. Res. **66**, 2263–2264.

Öpik, E., and S. F. Singer (1961), Distribution of density in a planetary exosphere, II., Phys. Fluids **4**, 221.

Pannekoek, A. (1922), Ionization in stellar atmospheres, Bull. Astron. Inst. Netherlands, No. 19.

Priester, W. (1961), Solar activity effect and diurnal variation in the upper atmosphere, J. Geophys. Res. **66**, 4143–4148.

Purcell, J., and R. Tousey (1960), The profile of solar hydrogen Lyman α, J. Geophys. Res. **65**, 370–372.

Serbu, G. P., R. E. Bourdeau, and J. L. Donley (1961), Electron temperature measurements on the Explorer VIII satellite, J. Geophys. Res. **66**, 4313–4315.

Spencer, N. W., L. H. Brace, and J. R. Carignan (1962), Electron temperature evidence for nonthermal equilibrium in the ionosphere, J. Geophys. Res. **67**, 157–176.

Taylor, H. A., H. Brinton, and C. R. Smith (1962), Instrumentation for atmospheric composition measurements, Proc. 8th Aerospace Instrumentation Symposium (Instrument Society of America, Pittsburgh).

Willmore, A. P., R. L. F. Boyd, and P. J. Bowen (1962), Some preliminary results of the plasma probe experiments on the Ariel satellite, Proc. Internat. Conf. on the Ionosphere, London, July 1962.

2. Theory of Magnetospheric Radio Scattering

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Associated with the suggestion by W. E. Gordon [1958] for measurement of the electron density in the magnetosphere by radar backscattering above the penetration frequency of the ionosphere, and the successful application of this method by K. L. Bowles [1961], numerous papers have appeared analyzing in detail the theory of this scattering phenomenon. Papers have been published by E. E. Salpeter [1960], J. P. Dougherty and D. T. Farley [1960], J. Renau [1960], J. A. Fejer [1960], T. Hagfors [1961], and O. Buneman [1962]. For a radar looking vertically upwards into the magnetosphere the echo is produced by vertically moving plasma waves of electron density in the magnetosphere with a wavelength equal to half that of the exploring radio wave. The returned energy is Doppler spread, and the frequency shift in the returned spectrum corresponds to the vertical velocity of the plasma wave in the magnetosphere according to the usual Doppler formula. Thus the frequency spectrum of the echo gives the velocity spectrum of vertically propagated plasma waves of electron density in the magnetosphere of wavelength equal to half the wavelength of the exploring radio wave.

When the wavelength is very large compared with the Debye length, the vertical plasma waves concerned are the upward and downward electron acoustic waves, together with the upward and downward ion acoustic waves, for which the electron density follows the ion density [Denisse and Delcroix, 1961]. On the other hand, when the wavelength is small compared with the Debye distance, the vertical plasma waves are gaussianly distributed in velocity about zero; the plasma waves then correspond to the gaussianly distributed vertical streams of thermic electrons, the relation between the waves and the streams being similar to that involved in a traveling wave tube or linear accelerator. We thus emerge, in the general case, with a backscatter spectrum rather like a partially resolved spectral doublet, with the maxima corresponding to vertically propagated ion acoustic waves; on each side of this main spectrum is a narrow line, separated from the transmitted frequency by roughly the plasma frequency, and corresponding to the vertically propagated electron acoustic waves.

The effect of the earth's magnetic field is to cause frequency modulation in the Doppler shift of the echo, corresponding to gyration of the charged particles round the magnetic field. When the magnetic field is at right angles to the line of sight, the principal effect is to split the backscatter spectrum into lines whose separatio 1 is the ionic gyrofrequency. However, as the magnetic field is turned away from the transverse position, the component of line-of-sight charge-velocity parallel to the magnetic field spreads the lines, and the spectrum quickly becomes a continuous spectrum similar to that for no magnetic field.

References

Bowles, K. L. (1961), Incoherent scattering by free electrons as a technique for studying the ionosphere and exosphere: Some observations and theoretical considerations, J. Res. NBS **65D** (Radio Prop.), 1–14.

Buneman (1962), J. Geophys. Res. **67**, 2050.

Denisse, J. F., and J. L. Delcroix (1961), Theory of Waves in Plasmas (Dunod, Paris).

Dougherty, J. P., and D. T. Farley (1960), Proc. Roy. Soc. A **259**, 79.

Fejer, J. A. (1960), Can. J. Phys. **38**, 1114.

Fejer, J. A. (1961), Can. J. Phys. **39**, 716.

Gordon, W. E. (1958), Proc. IRE **46**, 1824.

Hagfors, T. (1961), J. Geophys. Res. **66**, 1699.

Renau, J. (1960), J. Geophys. Res. **65**, 3631.

Salpeter, E. E. (1960), Phys. Rev. **120**, 1528.

3. Terrestrial Radio Noise

William Q. Crichlow and Robert T. Disney

1. Introduction

This section deals primarily with recent investigations of the composite noise at a particular receiving location which results from all terrestrial sources. A knowledge of the characteristics of this composite noise is necessary in order to evaluate its effects on the reception of radio signals. The principal type of noise to be considered originates in the atmosphere during lightning discharges, but under certain circumstances other types of noise may be important such as that originating from manmade sources, in the ionosphere, and the earth's magnetic or electrostatic field.

In addition to studies of the composite effects of all sources, measurements have been made of the waveforms and resulting spectra of individual spherics from lightning discharges. These measurements provide information on the propagation medium and assist in evaluating the combined spectral distribution of the energy to be expected from a number of simultaneous thunderstorms.

2. Worldwide Measurements

The worldwide radio noise recording network sponsored by the National Bureau of Standards has continued in operation, and the data are published quarterly [Crichlow et al., 1959–1962]. Two additional stations have been put in operation during this reporting period—one in Warrensburg, Mo., and the other aboard the *USNS Eltanin*, which is cruising in Antarctic waters. Measurements at all stations are made by means of the ARN–2 radio noise recorder, which provides an automatic record of three statistical moments of the noise—the average power, the average envelope voltage, and the average logarithm of the envelope voltage.

3. Amplitude-Probability Distribution

The amplitude-probability distribution of the noise envelope (APD) has been found to be extremely useful in determining the interference to various types of radio systems as discussed in the National Committee Report to the XIII General Assembly and summarized in a special report [URSI, 1962]. Using empirical methods, this APD can be represented with reasonable accuracy by means of the three statistical moments measured in the NBS network [Crichlow et al., 1960a], and families of typical curves have been published [Crichlow et al., 1960b]. Such an APD is applicable only to the receiver bandwidth in which the statistical moments were measured. Recent contributions to methods for predicting the APD for any specified bandwidth from the moments of the noise measured in a different bandwidth have been derived [Spaulding et al., 1962].

4. Worldwide Predictions

A number of studies have been in progress to test the validity of the worldwide noise predictions published by the International Radio Consultative Committee [CCIR, 1956].

Herman [1961] compared the CCIR predicted values of radio noise with subsequent noise measurements at four noise recording stations over the frequency range of 13 kc/s through 10 Mc/s. In general, good agreement was found. Largest disagreements were found where the predictions were based on extrapolations of data measured at other stations. Some explanations for the discrepancies were discussed.

More recently a detailed comparison was made between data measured at all temperate and tropical stations in the NBS network and the CCIR predictions. The results of the analysis were presented in the form of a supplement to the CCIR predictions and contained the following information:

(a) corrections as a function of frequency, time of day, and season,
(b) statistical information on the accuracy of the corrected values,
(c) statistical information on the fine structure of the noise,
(d) specific suggestions on the use of noise data in the solution of operational problems.

This supplement was adopted at an interim meeting of CCIR Study Group VI [CCIR, 1962].

Subsequent and more complete analysis of the data from all the stations in the NBS network has led to the preparation of a complete revision of the CCIR predictions which has been submitted for possible adoption by the CCIR at its Xth Plenary Assembly. This revision contains corrected noise charts of the world, each with an accompanying set of amplitude versus frequency curves as well as curves showing the variability of the noise and the statistical reliability of the predictions. Also presented is information on the fine structure of the noise in the form of amplitude-probability distributions. Expected values of galactic radio noise and manmade radio noise are shown on the amplitude versus frequency curves and, as confirmed by more recent measurements, have the same level and frequency dependence given in the previous CCIR predictions. Two examples illustrate the use of the revised predictions in the evaluation of system performance.

5. Ionospheric Effects

5.1. Changes in Atmospheric Noise Levels Associated With High-Altitude Thermonuclear Explosions

Not only are there variations of the received atmospheric radio noise due to natural changes in the ionosphere, but also variations have been observed due to "manmade" changes in the ionosphere. Samson [1963] found that a comparison of radio noise data for August 1958, with that for later years shows that the Johnston Island nuclear explosions on August 1 and 12, 1958, affected the atmospheric radio noise over a wide area in the Pacific region. Graphs of the midnight noise level at several frequencies from 13 kc/s to 5 Mc/s illustrate apparent noise anomalies at Cook, Australia; Ohira, Japan; Byrd Station, Antarctica; and Singapore. These anomalies resemble in several respects the well-marked effects previously noted [Samson, 1959; 1960] at Kekaha, Hawaii.

5.2. Synchrotron Emission From Energetic Electrons in the Upper Atmosphere

The possibility of detecting radio noise originating in the upper atmosphere by the synchrotron emission process (i.e., due to the spiralling of very energetic electrons around the magnetic field lines) was discussed by Dyce and Nakada [1959]. Observations by Ochs et al. [1963] using the large 50 Mc/s incoherent scatter antenna at Jicamarca, Peru, failed to reveal any detectable synchrotron emission at that frequency arising from the natural Van Allen belt electrons. However, strong synchrotron emissions were noted at various equatorial latitudes following the high-altitude thermonuclear explosion of July 9, 1962 [Ochs et al., 1963; Dyce and Horowitz, 1963]. At higher magnetic latitudes, and somewhat lower frequencies, Egan and Peterson [1960] have reported the occasional occurrence of auroral radio noise attributable to synchrotron emission from energetic electrons of natural origin.

5.3. Thermal Noise from the Ionosphere

Because the ionosphere acts as an absorber of radio waves, it can also act as an emitter of thermal radio noise. Observations of the thermal noise level on a 2.89 Mc/s dipole antenna have been made near College, Alaska [Little et al., 1961]. In the absence of cosmic noise and other interference, equivalent midday antenna temperatures during the winter were in the range 200 to 250 °K, in good agreement with the temperature of the neutral gas in the lower part of the D region. Nighttime observations during aurora indicated that the temperature of the electrons in the lower part of the absorbing region is not markedly affected by the presence of the aurora.

6. Waveforms and Fields, ELF, VLF, and LF

Taylor [1963] has examined the groundwave portion of atmospheric waveforms to determine various characteristics of the radiation field from lightning discharges. A large number of representative waveforms were selected from thunderstorms in the Oklahoma and North Texas area. The average amplitude and phase spectra from 1 to 100 kc/s were presented for several groups of atmospherics. Various other relationships involving the total radiated energy, peak field strength, first half-cycle length, spectral amplitude peak, and frequency of spectral peak were presented.

Watt [1960] calculated the expected ELF fields produced from models assumed to be typical of "long" and "short" discharges, and the calculated values were found to agree well with observed fields. The vertical electric field decreases very slowly with distance from the source for distances comparable to the discharge channel heights. From 4 to 20 km a $1/d^3$ relation is observed, and beyond 30 km a complicated relation with distance is found due to ionospheric effects. The models employed indicate that below 300 c/s, "long" discharges produce much more energy than "short" discharges, and that intercloud and intracloud discharges may produce as much energy as cloud to ground discharges.

Pierce [1960] and Wait [1960] discussed the relationship of observed atmospherics at ELF to the electric and magnetic fields. In particular, Wait [1960] gave a theoretical treatment of ELF propagation and suggested that certain observed characteristics of ELF waveforms might be attributed to the inclination of the current channel in the lightning discharge.

Campbell [1960] observed the transition frequency of natural signals from sferics slow tails to geomagnetic micropulsations to be between 2.0 and 0.2 c/s. Micropulsations with periods of 5 to 30 sec have characteristics which closely relate to solar terrestrial disturbance phenomena. The low latitude diurnal amplitude variation has maximums at 0945 and 1000 LMT. Similar groups of oscillations appear in Alaska and California. Simultaneous pulsation of λ3914 aurora and magnetic field micropulsations have been observed in Alaska.

References

Campbell, W. H. (July–Aug. 1960), Natural electromagnetic energy below the ELF range, J. Res. NBS **64D** (Radio Prop.), No. 4, 409–411.

CCIR Rept. 65 (1956), Revision of radio noise data, VIII Plenary Assembly.

CCIR (May 1962), Proposed modifications and additions to Rept. 65, Doc. VI/115, Study Group VI Interim Meeting, Geneva.

Crichlow, W. Q., R. T. Disney, and M. A. Jenkins (1959–1962), Quarterly radio noise data, NBS Tech. Note Nos. 18 through 18–14.

Crichlow, W. Q., C. J. Roubique, A. D. Spaulding, and W. M. Beery (Jan. 1960a), Determination of the amplitude-probability distribution of atmospheric radio noise from statistical moments, J. Res. NBS **64D** (Radio Prop.). No. 1, 49–56.

Crichlow, W. Q., A. D. Spaulding, C. J. Roubique, and R. T. Disney (Nov. 1960b), Amplitude-probability distributions for atmospheric radio noise, NBS mono. 23.

Dyce, R. B., and M. P. Nakada (1959), On the possibility of detecting synchrotron radiation from electrons in the Van Allen belts, J. Geophys. Res. **64,** No. 9, 1163–1168.

Dyce, R. B., and S. Horowitz (1963), Measurements of synchrotron radiation at central Pacific sites, J. Geophys. Res. **68,** No. 3, 713–721.

Egan, R. D., and A. M. Peterson (1960), Auroral noise at HF, J. Geophys. Res. **65,** No. 11, 3830–3832.

Herman, J. R. (Nov.–Dec. 1961), Reliability of atmospheric radio noise predictions, J. Res. NBS **65D** (Radio Prop.), No. 6, 565–574.

Little, C. G., G. M. Lerfald, and R. Parthasarathy (Dec. 1961), Some observations of 2.89 Mc/s equivalent antenna temperatures at the auroral zone, J. Atmospheric Terrest. Phys. **23,** 275–286.

Ochs, G R., D. T. Farley, Jr., K. L. Bowles, and P. Bandyopadhay (1963), Observations of synchrotron radio noise at the magnetic equator following the high altitude nuclear explosion of July 9, 1962, J. Geophys. Res. **68,** No. 3, 701–711.

Pierce, E. T. (July–Aug. 1960), Some ELF phenomena, J. Res. NBS **64D** (Radio Prop.), No. 4, 383–386.

Samson, C. A. (Aug. 15, 1959), Effects of atomic tests on radio noise, Nature **184,** 538.

Samson, C. A. (Jan. 1960), Effects of high-altitude nuclear explosions on radio noise, J. Res. NBS **64D** (Radio Prop.), 37–40.

Samson, C. A. (May 1, 1963), Radio noise anomalies in August 1958, J. Geophys. Res. **68.**

Spaulding, A. D., W. Q. Crichlow, and C. J. Roubique (Nov.–Dec. 1962), Bandwidth conversion of the amplitude-probability distribution function from the first two moments for atmospheric radio noise, J. Res. NBS **66D** (Radio Prop.), No. 6, 713–732.

Taylor, W. L. (1963), Radiation field characteristics of lightning discharges in the band 1 kc/s to 100 kc/s, J. Res. NBS **67D** (Radio Prop.) (to be published).

URSI Special Rept. No. 7 (1962), The measurement of characteristics of terrestrial radio noise (Elsevier Publ. Co.).

Wait, J. R. (July–Aug. 1960), Mode theory and the propagation of ELF radio waves, J. Res. NBS **64D** (Radio Prop.), No. 4, 387–404.

Watt, A. D. (Sept.–Oct. 1960), ELF electric fields from thunderstorms, J. Res. NBS **64D** (Radio Prop.), No. 5, 425–433.

4. Geomagnetism and the Magnetosphere

A. J. Dessler

1. Introduction

The geomagnetic field, in its gross features, is similar to the field of a uniformly magnetized sphere. Such a simple model is inadequate in detail, however, for two principal reasons. First, the relatively steady main field contains, in addition to its predominant dipole component, important contributions from higher multipoles and numerous irregularities of local origin. The most accurate simple representation of the field is given by the eccentric dipole, which is both tipped relative to the earth's axis and displaced from its center. Second, the field varies continuously with time in an irregular manner.

The earth's main magnetic field is commonly supposed to originate by dynamo action in the fluid motion of the molten metallic core of the earth. This fluid motion is unstable; it changes slightly from year to year to produce the secular variation, which requires hundreds of years to produce a significant change in the geomagnetic field. Transient variations, which take place in times less than one year (some occurring in a small fraction of a second) have their sources outside the earth, and are produced chiefly by the interaction between solar plasma and the geomagnetic field.

Scientific observations of geomagnetic field have been made for the past several hundred years. For example, the secular variation was discovered in 1635 by means of data obtained as early as 1580. The transient variations were discovered in 1722. The first magnetic observatories were constructed during the late eighteenth century for the purpose of making systematic observations over widely separated geographic positions. Since that time, enormous amounts of data have been gathered. An outstanding job of describing, summarizing, and analyzing the data to 1940 may be found in the two-volume set, *Geomagnetism,* by Chapman and Bartels [1940].

Recent geomagnetic research has been directed mainly toward an understanding of the transient variations. The greatest progress in this direction has come about through the application of the principles of hydromagnetism.

The transient variations arise from changing electric currents flowing in the ionosphere or the magnetosphere or from hydromagnetic waves generate by interactions between the geomagnetic field and ionized gas (plasma) moving out from the sun. This gas, which is thought to flow radially outward, is referred to as the solar wind. This solar wind will push into the geomagnetic field roughly to the point where the kinetic energy density of the solar wind is equal to the magnetic-field energy density and form an elongated cavity around the earth. The geomagnetic field is contained inside this cavity, which is often called the "magnetosphere."

Of the many observed types of transient variations, the largest (and most carefully studied) are diurnal variations and geomagnetic storms. The diurnal variation is attributed to tidal motion in the ionosphere. At a given location, the diurnal variation is reasonably predictable and usually involves field changes of the order of 0.1 percent of the total field. The geomagnetic storm, while frequently following a general pattern, is much less predictable, both as to time of occurrence and detailed characteristics.

Although the application of the principles of hydromagnetism and plasma physics have led to many valuable insights regarding geomagnetic phenomena, much is left to be explained. In particular, the aurora is evidently an intimate feature of geomagnetic storms. However, no widely accepted auroral theory has yet been proposed. Since the aurora is such a dramatic effect, and since it dissipates such a large amount of energy whose source is not understood, we should remain suspicious of any theory of geomagnetic storms that does not also explain the aurora.

2. The Solar Wind and the Magnetosphere

The solar corona is so hot that the solar gravitational field cannot contain it. This solar plasma, which expands radially away from the sun, is called the solar wind, following Parker's [1958a] terminology. The solar wind impinges against the geomagnetic field and confines it within a cavity. The name magnetosphere has been suggested for the regions of the geomagnetic field where the motions of geomagnetic field have dominant control over the motions of low-energy plasma and fast charged particles. This name, suggested by Gold [1959], is now common usage. In its usual sense, the magnetosphere is taken to be the region between the top of the ionospheric E region (~ 140 km altitude) and the outer boundary of the geomagnetic field—usually at geocentric distances greater than 10 R_E (the symbol R_E is used for earth radii).

The first quantitative theoretical treatment of the expansion of the solar corona is due to Parker [1958a] The consequences of a 10^6 °K corona were also examined by Chamberlain [1960 and 1961]. Chamberlain, too, found that, if the solar magnetic field is neglected, the corona must expand. Chamberlain assumed a small total heat input into a thin region at the base of the corona and derived an "evaporative" solar wind (or solar breeze) velocity of 20 km/s. Parker [1958b and 1960], on the other hand, assumed a much greater coronal heat input extending over a distance of ~10 solar radii and derived solar wind velocities of the order of 500 km/s. Subsequent theoretical work by Noble and Scarf [1962] clarified the differences between Parker's and Chamberlain's approach to the problem.

It has been argued, on the basis of cosmic radiation data [Ahluwalia and Dessler, 1962], and on theoretical considerations of the solar magnetic field [Axford, Dessler, and Gottlieb, 1963], that the solar wind velocity must be greater than 100 km/s. The Mariner II [Neugebauer and Snyder, 1962] and Explorer X [Bridge, Dilworth, Lazarus, Lyon, Rossi, and Scherb, 1961] plasma probe results are in agreement with these findings and show that the extensive coronal heating assumed by Parker must more nearly represent the structure of the solar corona than Chamberlain's model.

The solar wind strikes the geomagnetic field and deforms it. Approximate solutions have been obtained by Beard [1960 and 1962] for the case of a magnetic-field-free plasma striking a dipole magnetic field. Beard's method has been applied by Spreiter and Briggs [1962a]. However, they reduced the plasma pressure for elastic reflection by a factor 2, "under the mistaken impression that charge separation in the boundary somehow alters the condition for conservation of momentum" [Parker, 1962]. This error was corrected in a subsequent publication [Spreiter and Briggs, 1962b]. A fundamentally different approach to the problem of the shape of the magnetosphere in the solar wind has been developed by Midgley and Davis [1962], but their results are not significantly different from that obtained by Beard, or Spreiter and Briggs.

Recent considerations by Kellogg [1962] (and simultaneously by Axford [1962], Canada) of the effect of the solar (i.e., interplanetary) magnetic field, which is imbedded in the solar wind, on the interaction between the solar wind and the magnetosphere, casts doubt on the applicability of this previous work that neglected the interplanetary magnetic field. The effect of an interplanetary field in the solar plasma is to make the interplanetary medium capable of propagating hydromagnetic waves. The solar wind is supersonic relative to the interplanetary hydromagnetic wave velocity. Kellogg and Axford argue that there should be a standing hydromagnetic shock wave in front of the magnetosphere. The presence of this shock, the compressed gas between the shock and the magnetosphere (the magnetosheath), and the interplanetary magnetic field, make a reexamination of the boundary conditions governing the shape of the magnetosphere imperative.

It has been argued, from examination of ordinary surface magnetometer data [Dessler, 1961] and of satellite and space probe data [Dessler, 1962; Cahill and Amazeen, 1963] that the surface of the magnetosphere (the magnetopause) is stable. Some early experimental work was erroneously interpreted as indicating that the magnetopause was unstable and was generating hydromagnetic waves [Sonett, Smith, and Sims, 1960].

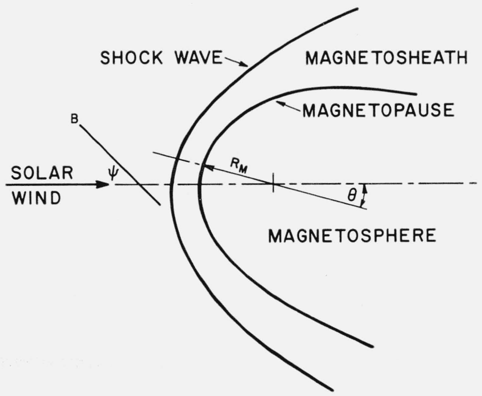

FIGURE 1
Sketch illustrating the interaction of the solar wind with the geomagnetic field [Dessler and Fejer, 1963].

The general configuration of the magnetosphere and shock wave as sketched in figure 1 (taken from a manuscript by Dessler and Fejer [1963]) is consistent with nearly all experimental data and theoretical ideas available thus far.

3. Quiet-Day Ring Current

Some nondipolar characteristics were detected in the earth's magnetic field near the apogee of Explorer VI and these characteristics were apparently confirmed by a few scattered data points from Pioneer V. Unfortunately, these measurements were incorrectly interpreted as indicating the presence of a large-scale, quiet-day, ring current [Sonett, Smith, and Sims, 1960; Sonett, Smith, Judge, and Coleman, 1960; Smith, Coleman, Judge and Sonett, 1960]. Subsequent, definitive, magnetometer data from Explorer X [Heppner, Ness, Scearce, and Skillman, 1963] and Explorer XII [Cahill and Amazeen, 1963] show that no such quiet-day ring current exists. There now seems to be some agreement on this point between the various experimenters [Smith, 1962]. However, it should be noted that any trapped radiation contributes to a ring current. Thus, the Van Allen radiation belt constitutes a (weak) ring current [Dessler and Vestine, 1960].

Detailed calculations on the magnetic effects of trapped particles ring currents have been carried out. Some of these calculations set up model radiation belts to fit the nonexistent quiet-day ring current [Akasofu and Chapman, 1961; Akasofu, Cain, and Chapman, 1961]—these calculations, however, are still of value in that they illustrate the method for carrying out such calculations and give one an intuitive insight regarding the magnetic effects of trapped particle belts. The presence of an intense flux of low-energy trapped protons in the outer zone of the Van Allen radiation belt was recently announced by Davis and Williamson [1962]. This observed trapped-radiation creates a ring current that has a small but significant effect on the earth's magnetic field. A calculation of the effect of this ring current has been carried out by Akasofu, Cain, and Chapman [1962].

4. Geomagnetic Storm Effects

A most striking effect of magnetic storms on the magnetosphere has been discovered by Carpenter [1962a and 1962b]. Evidence from whistler delay times indicates that during or immediately following intense magnetic activity, $K_p \gtrsim 6$, the electron density in the outer part of the magnetosphere decreases by a factor of about 4. No plausible explanations have been advanced to account for this phenomenon.

Hydromagnetic concepts have been applied to the problems of the geomagnetic storm with remarkable success considering the number of complicating features that have been generally ignored. Dessler, Francis, and Parker [1960] have offered a hydromagnetic model that can account for the 1 to 6 min sudden commencement (*SC*) rise time. Wilson and Sugiura [1961] have pointed out that some of the worldwide feature of the *SC*—particularly the reverse *SC* at high latitudes—can be explained very simply if the impact of the interplanetary shock on the magnetosphere (which initiates the *SC*) generates two counter-rotating, circularly polarized, hydromagnetic waves. The sense of rotation of these waves changes along approximately the noon-midnight meridian. The concept that the *SC* is propagated to the earth's surface by hydromagnetic waves has received strong independent support from the observations of a sudden increase in energetic particle radiation outside the magnetosphere, followed in a few minutes by an *SC* [Hoffman, Davis, and Williamson, 1962]. The time delay is attributed to the hydromagnetic wave propagation time.

The main phase of geomagnetic storms is usually assumed to be due to a ring current formed by a belt of trapped protons, although at least one prominent worker believes the trapped particles to be electrons [Singer, 1962]. No adequate mechanism for injecting energetic particles directly from the solar wind into the magnetosphere has ever been put forth; also, there are specific objections to such a process [Dessler, 1961; Dessler, Hanson, and Parker, 1961]. An alternate mechanism has been suggested in which the main-phase proton ring current is created by hydromagnetic shock-wave acceleration of the ambient protons that constitute the normal protonosphere [Dessler, Hanson, and Parker, 1961; Kern, 1962].

One of the interesting features of the trapped proton ring current is that it is removed by charge-exchange collisions with atomic hydrogen in the geocorona. Johnson has pointed out that the geocorona must be more dense near sunspot minimum than sunspot maximum [Johnson, 1961] (by about a factor 3 at 4 R_E). Therefore, if the ring current is removed by charge-exchange, the recovery time constant should be about 3 times less at sunspot minimum than sunspot maximum. An analysis of magnetograms by Matsushita [1962] has given a result in agreement with this prediction.

5. Short Period Transient Variations

One of the most promising fields for future geomagnetic research is in the study of magnetic fluctuations with periods less than 10 min and greater than 0.1 sec. The aim of this research is to understand how the magnetosphere oscillates and how charged particle and auroral effects contribute to short period geomagnetic activity.

A review and discussion of the purely hydromagnetic aspects of this problem has been given by MacDonald [1961]. In this paper, MacDonald has, as have previous workers, neglected the transfer of energy from one hydromagnetic mode to another (mode mixing). It is not known how important these nonlinear coupling terms may be.

A different approach to the problem of the origin of the short period transient variations is that they are due to bunches of trapped particles bouncing back and forth in the geomagnetic field. This idea has been most actively pursued by Campbell and coworkers [Campbell, 1959; Campbell, 1960; Campbell 1961; Campbell and Leinbach, 1961; Campbell and Rees, 1961], and by Tepley and Wentworth [1962a and 1962b].

Other topics that have been considered are the dissipation of hydromagnetic wave energy as a possible mechanism to provide energy for the aurora [Dessler and Hanson, 1961], the propagation and dissipation of hydromagnetic wave energy in the lower ionosphere [Fejer, 1960; Francis and Karplus, 1960; Karplus Francis, and Dragt, 1962], and the scattering of trapped radiation by hydromagnetic waves [Dragt, 1961; Wentzel, 1962].

References

Ahluwalia, H. S., and A. J. Dessler (1962), Diurnal variation of cosmic radiation intensity produced by a solar wind, Planet. Space Sci. **9,** 195.

Akasofu, S. I., and S. Chapman (1961), The ring current, geomagnetic disturbance, and the Van Allen radiation belts, J. Geophys. Res. **66,** 1321.

Akasofu, S. I., J. C. Cain, and S. Chapman (1961), The magnetic field of a model radiation belt, numerically computed, J. Geophys. Res. **66,** 4013.

Akasofu, S. I., J. C. Cain, and S. Chapman (1962), The magnetic field of the quiet-time proton belt, J. Geophys. Res. **67,** 2645.

Axford, W. I. (1962), Interaction between the solar wind and the earth's magnetosphere, J. Geophys. Res. **67,** 3791.

Axford, W. I., A. J. Dessler, and B. Gottlieb (May 1963), Termination of solar wind and solar magnetic field, Astrophys. J.

Beard, D. B. (1960), The interaction of the terrestrial magnetic field with the solar corpuscular radiation, J. Geophys. Res. **65,** 3559.

Beard, D. B. (1962), The interaction of the terrestrial magnetic field with the solar corpuscular radiation, 2, Second-order approximation, J. Geophys. Res. **67,** 477.

Bridge, H. S., C. Dilworth, A. J. Lazarus, E. F. Lyon, B. Rossi, and F. Scherb (1961), Direct observations of the interplanetary plasma, Proc. Kyoto Conference on Cosmic Rays and the Earth Storm, Kyoto, Japan.

Cahill, L. J., and P. G. Amazeen (1963), The boundary of the geomagnetic field, J. Geophys. Res. **68.**

Campbell, W. H. (1959), Studies of magnetic field micro-pulsations with periods of five to thrity seconds, J. Geophys. Res. **64,** 1819.

Campbell, W. H (1960), Magnetic micropulsations., pulsating aurora, and ionospheric absorption, J. Geophys. Res. **65,** 1833.
Campbell, W. H. (1961), Magnetic field micropulsations and electron bremsstrahlung, J. Geophys. Res. **66,** 3599.
Campbell, W. H., and H. Leinbach (1961), Ionospheric absorption at times of auroral and magnetic pulsations, J. Geophys. Res. **66,** 25.
Campbell, W. H., and M. H. Rees (1961), A study of auroral coruscations, J. Geophys. Res. **66,** 41.
Carpenter, D. L. (1962a), New experimental evidence of the effect of magnetic storms on the magnetosphere, J. Geophys. Res. **67,** 135.
Carpenter, D. L. (1962b), Electron-density variations in the magnetosphere deduced from whistler data, J. Geophys. Res. **67,** 3345.
Chamberlain, J. W. (1960), Interplanetary Gas, II. Expansion of a model solar corona, Astrophys. J. **131,** 47.
Chamberlian, J. W. (1961), Interplanetary Gas, III. Hydrodynamic model of the corona, Astrophys. J. **133,** 675.
Chapman, S., and J. Bartels (1940), Geomagnetism (Oxford University Press, London).
Davis, L. R., and J. M. Williamson (1962), Low-energy trapped protons, paper presented at Third COSPAR International Space Science Symposium, Washington, D.C., April 30–May 9, 1962.
Dessler, A. J. (1961), The stability of the interface between the solar wind and the geomagnetic field, J. Geophys. Res. **66,** 3587.
Dessler, A. J. (1962), Further comments on stability of interface between solar wind and geomagnetic field, J. Geophys. Res. **67,** 4982.
Dessler, A. J., and J. A. Fejer (1963), Interpretation of K_p index and *M*-region geomagnetic storms, to be published in Planet. Space Sci.
Dessler, A. J., W. E. Francis, and E. N. Parker (1960), Geomagnetic storm sudden-commencement rise times, J. Geophys. Res. **65,** 2715.
Dessler, A. J., and W. B. Hanson (1961), Possible energy source for the aurora, Astrophys. J. **134,** 1024.
Dessler, A. J., W. B. Hanson, and E. N. Parker (1961), Formation of the geomagnetic storm main-phase ring current, J. Geophys. Res. **66,** 3631.
Dessler, A. J., and E. H. Vestine (1960), Maximum total energy of the Van Allen radiation belt, J. Geophys. Res. **65,** 1069.
Dragt, A. J. (1961), Effect of hydromagnetic waves on the lifetime of Van Allen radiation protons, J. Geophys. Res. **66,** 1641.
Fejer, J. A. (1960), Hydromagnetic wave propagation in the ionosphere, J. Atmospheric Terrest. Phys. **18,** 135.
Francis, W. E., and R. Karplus (1960), Hydromagnetic waves in the ionosphere, J. Geophys. Res. **65,** 3593.
Gold, T. (1959), Motions in the magnetosphere of the earth, J. Geophys. Res. **64,** 1219.
Heppner, J. P., N. F. Ness, C. S. Scearce, and T. L. Skillman (1963), Explorer X magnetic field measurements, J. Geophys. Res. **68,** 1.
Hoffman, R. A., L. R. Davis, and J. M. Williamson (1962), Protons of 0.1 to 5 Mev and electrons of 20 kev at 12 earth radii during sudden commencement on September 30, 1961, J. Geophys. Res. **67,** 5001.
Johnson, F. S. (1961), Structure of the upper atmosphere, Ch. 1, Satellite Environment Handbook, ed. F. S. Johnson, 155 (Stanford Univ. Press, Stanford, Calif.).
Karplus, R., W. E. Francis, and A. J. Dragt (1962), The attenuation of hydromagnetic waves in the ionosphere, Planet. Space Sci. **9,** 771.
Kellogg, P. J. (1962), Flow of plasma around the earth, J. Geophys. Res. **67,** 3805.
Kern, J. W. (1962), A note on the generation of the main-phase ring current of a geomagnetic storm, J. Geophys. Res. **67,** 3737.
MacDonald, G. J. F. (1961), Spectrum of hydromagnetic waves in the exosphere, J. Geophys. Res. **66,** 3639.
Matsushita, S. (1962), On geomagnetic sudden commencements, sudden impulses, and storm durations, J. Geophys. Res. **67,** 3753.
Midgley, J. E., and L. Davis (1962), Computation of the bounding surface of a dipole field in a plasma by a moment technique, J. Geophys. Res. **67,** 499.
Neugebauer, M., and C. Snyder (1962), Solar plasma experiment, Science **138,** 1095.
Noble, L. M., and F. L. Scarf (1962), Hydrodynamic models of the solar corona, J. Geophys. Res. **67,** 4577.
Parker, E. N. (1958a), Interactions of the solar wind with the geomagnetic field, Phys. Fluids **1,** 171.
Parker, E. N. (1958b), Dynamics of the interplanetary gas and magnetic fields, Astrophys. J. **128,** 664.
Parker, E. N. (1960), The hydrodynamic theory of solar corpuscula rradiation and stellar winds, Astrophys. J. **132,** 821.
Parker, E. N. (1962), Dynamics of the geomagnetic storm, Space Sci. Rev. **1,** 62.
Singer, S. F. (1962), Nature of magnetic storm belt particles, Electrons or protons, J. Geophys. Res. **67,** 1658.
Smith, E. J. (1962), A comparison of Explorer VI and Explorer X magnetometer data, J. Geophys. Res. **67,** 2045.
Smith, E. J., P. J. Coleman, Jr., D. L. Judge, and C. P. Sonett (1960), Characteristics of the extraterrestrial current system: Explorer VI and Pioneer V, J. Geophys. Res. **65,** 1858.
Sonnett, C. P., E. J. Smith, D. L. Judge, and P. J. Coleman, Jr. (1960), Current systems in the vestigial geomagnetic field: Explorer VI, Phys. Rev. Letters **4,** 161.
Sonnett, D. P., E. J. Smith, and A. R. Sims (1960), Survey of the distant geomagnetic field: Pioneer I and Explorer VI, Space Research, ed. H. Kallmann-Bijl, 921–937 (North Holland Publ. Co., Amsterdam).
Spreiter, J. R., and B. R. Briggs (1962a), The theoretical determination of the form of the boundary of the solar corpuscular stream produced by interaction with the magnetic dipole field of the earth, J. Geophys. Res. **67,** 37.
Spreiter, J. R., and B. R. Briggs (1962b), On the choice of conditions to apply at the boundary of the geomagnetic field in the steady-state Chapman-Ferraro problem, J. Geophys. Res. **67,** 2983.
Tepley, L. R., and R. C. Wentworth (1962), Hydromagnetic emissions, X-ray bursts, and electron bunches, I. Experimental results, J. Geophys. Res. **67,** 3317.
Wentworth, R. C., and L. R. Tepley (1962), Hydromagnetic emissions, X-ray bursts, and electron bunches, II. Theoretical interpretation, J. Geophys. Res. **67,** 3335.
Wentzel, D. G. (1962), Hydromagnetic waves in the trapped radiation, Effects on protons above the proton belt, J. Geophys. Res. **67,** 485.
Wilson, C. R., and M. Sugiura (1961), Hydromagnetic interpretation of sudden commencements of magnetic storms, J. Geophys. Res. **66,** 4097.

5. Theory of Radio and Hydromagnetic Wave Propagation in the Magnetosphere

H. G. Booker

A number of investigations have been made bearing on the guidance of radio, audio, and hydromagnetic waves round the lines of flux of the earth's magnetic field. R. L. Smith [1960] has examined the radiation in a homogeneous magnetoplasma from a point source of electromagnetic waves at frequencies less than the electronic gyrofrequency. He neglected the effect of ions and the effect of pressure gradients. He showed that the radiation is confined to a cone that decreases from 90° to 11° as the wave frequency decreases from the electronic gyrofrequency to 0.189 times the electronic gyrofrequency. The cone angle then increases to 19°29′ as the frequency tends to zero, but it must be remembered that neglect of ions restricts the theory to frequencies large compared with the ionic gyrofrequency.

In a different frequency range the same problem has been treated by G. MacDonald [1961]. MacDonald includes the effect of ions and the effect of pressure gradients, but makes the usual MHD approximations that restrict his analysis to frequencies small compared with the ionic gyrofrequency. His analysis incorporates the acoustic wave in addition to the ordinary and extraordinary waves. He refers to these three waves as a pressure wave, a vorticity wave and a transverse wave. He verifies the usual MHD result that the vorticity wave is propagated one-dimensionally along the lines of flux of the imposed magnetic field. It should be noted, however, that this means that a point source radiating the vorticity mode does so in a cone around the direction of the magnetic field and that the angle of this cone tends to zero as the frequency tends to zero. MacDonald then modifies the theory to include the effect of a gravitational field, maintaining the wave frequency small compared with the ionic gyrofrequency. He shows that the previously nondispersive MHD waves are now dispersive. The dispersion is intimately associated with the resonant frequency of a horizontal slab of plasma subject to vertical displacement in an isothermal atmosphere. When the slab is displaced downwards, buoyancy predominates and tends to restore it, whereas when the slab is displaced upwards, gravity predominates and tends to restore it. The period of oscillation varies from ten minutes low in the magnetosphere to more than a day far out in the magnetosphere, and the corresponding frequency plays an important part in the dispersion phenomena. Special attention is paid to the cases where the magnetic field is either parallel to the gravitational field, or perpendicular to it.

Using the ray theory of propagation in a doubly refracting medium, I. Yabroff [1961] has calculated ray paths in the magnetosphere at a number of whistler frequencies for several model magnetospheres. In each case it was assumed that the ray starts vertically upwards into the magnetosphere. The rays show significant tendency to follow the direction of the earth's magnetic field, but important departures occur. While the ray often returns to the surface of the earth in the opposite hemisphere, there is significant lack of symmetry about the equatorial plane. Furthermore, when the ray returns to low levels in the magnetosphere, the direction of phase propagation is often radically different from vertical, with the result that reflected energy would not even approximately return along the same path. The conclusion is that field-alined columns of ionization are required to explain the remarkable echoing properties of whistlers and the lack of divergence frequently observed.

The ray theory of whistler trapping in field-alined columns of enhanced ionization has been studied by R. L. Smith, R. A. Helliwell, and I. W. Yabroff [1960] and by R. L. Smith [1961]. They consider a uniform magnetic field with no variation of electron density along the magnetic field but with an appropriate variation of electron density transverse to the magnetic field. This variation has a maximum along a particular line of flux and falls off sideways from this line to a uniform value at large distances. A ray crossing the line of maximum electron density at an angle θ_0 can be refracted in such a way as to follow a sinuous path about this line of flux. To achieve such trapping for a given value of θ_0 and for a given frequency less than the electronic gyrofrequency a certain minimum value is required for the fractional excess of the maximum electron density over the background value. This enhancement is calculated as a function of θ_0 and as a function of frequency for all frequencies less than the electronic gyrofrequency (neglecting the effect of ions). Only small enhancements are required for small values of θ_0.

R. M. Gallet and W. F. Utlaut [1961] have applied the ray theory of trapping by field-alined ionization in the magnetosphere in connection with experiments they have carried out at a frequency somewhat above the penetration frequency of the ionosphere. The experiment used a modified oblique-incidence ionospheric sounder operating at 13.7 Mc/s in geomagnetic latitude 50.2°. The objective of the experiment was to see whether it is possible for a field-alined duct in the magnetosphere to guide HF waves from one hemisphere to the other and back. For various time-intervals stretching over a period of several months echoes were in fact obtained at ranges varying from 20,000 to 27,600 km. It has been debated whether these echoes were obtained by propagation through ducts in the magnetosphere or by round-the-world propagation between the earth and the ionosphere. The present conclusion is that a more definitive experiment is required.

As an alternative to the ray theory of propagation by field-alined irregularities in the magnetosphere use may be made of the wave-guide mode theory. There is a close relationship between the two theories. However, the ray theory assumes that there is a large number of wave-guide modes trapped in the duct so that the crossing waves associated with all these modes constitute a substantially continuous angular spectrum of waves. The mode theory not only permits consideration of a situation in which only one or two modes are trapped in the duct, but even permits consideration of a situation in which all modes leak from the duct. If one is searching for the minimum requirements for trapping, it is the mode theory that is required. The mode theory has been applied by Booker [1962] to a situation involving a discontinuity of ionization density at a surface formed by rotating a particular line of magnetic flux round the magnetic axis of the earth. Such a surface of discontinuity can form what is known in acoustics as a whispering gallery. Another example of an electromagnetic whispering gallery occurs at the surface of the earth under conditions of tropospheric duct propagation. It is the mode theory of tropospheric duct propagation [Booker and Walkinshaw, 1946] that Booker has adapted for study of magnetospheric duct propagation. A calculation is made of the smallest fractional change of ionization density at the assumed magnetospheric surface of discontinuity required to avoid serious leakage of the lowest wave-guide mode. This is done by insuring that the mode involves incidence upon the interface at an angle more glancing than the critical angle for total internal reflection. The track width of the mode is calculated as in the case of tropospheric duct propagation. From this information it is possible to estimate not only the minimum strength of field-alined irregularities required to guide electromagnetic waves around the lines of flux of the earth's magnetic field but also the minimum transverse scale for which the guiding is effective. It is for magnetospheric ducts whose width is large compared with the track width calculated for the lowest mode that ray theory is applicable.

Booker has assumed that propagation in a magnetospheric duct is sufficiently close to the direction of the magnetic field that the longitudinal approximation to the magneto-ionic theory may be used. However, he has included the effect of ions, so that calculations can be made for the ordinary and extraordinary waves over the entire range of frequencies from radio, through audio, to hydromagnetic frequencies. For longitudinal propagation there is an outer zone of propagation in the magnetosphere that, in the HF band, corresponds to propagation on the top side of the ionosphere. This outer zone of propagation is pushed steadily outwards through the magnetosphere to indefinitely large distances from the earth as the frequency is decreased. For frequencies less than the electronic gyrofrequency at ionospheric levels, there is also an inner zone of propagation for the wave whose polarization is righthanded about the direction of the earth's magnetic field. This inner zone is the region where the electronic gyrofrequency exceeds the fixed wave frequency under consideration. It is in the inner zone for propagation for the righthand wave that whistler propagation takes place. At frequencies less than the ionic gyrofrequency at ionspheric levels, there is an inner zone of propagation for the wave whose polarization is lefthanded about the direction of the earth's magnetic field. This is the region where the ionic gyrofrequency exceeds the fixed wave frequency under consideration. It is in this inner zone of propagation for the lefthand wave that the propagation of both waves tends to that discussed by Alfven [1953]. At hydromagnetic and audio frequencies we are usually discussing propagation in the inner zone, whereas in the HF band above the ionosphere we are discussing propagation in the outer zone.

Booker shows that, for a given line of flux of the earth's magnetic field, there are about five decades of frequency over which guidance is possible for comparatively small fractional changes of ionization density transverse to the magnetic field. This frequency range slides down in frequency by about three decades as one moves from low to high latitude lines. Guidance disappears at sufficiently high radiofrequencies because the magnetosphere then behaves substantially like free space. Guidance disappears at sufficiently low hydromagnetic frequencies because the transverse scale of the guiding structure required is too large to be accommodated in the magnetosphere. Guiding is unlikely much above 10 Mc/s or much below 1 c/s.

M. S. V. Gopal Rao and H. G. Booker [1963] have applied ray theory to examine under what circumstances a wave propagating along an inhomogeneous magnetic field in an inhomogeneous plasma has the ray curvature necessary to follow the magnetic field. In general, a gradient of ionization density transverse to the magnetic field is required to achieve this condition, and they calculate the necessary gradient over a wide range of wave frequency and plasma frequency.

References

Alfven, H. (1953), Cosmical Electrodynamics (Oxford Univ. Press).

Booker, H. G. (1962), J. Geophys. Res. **66,** 4135.

Booker, H. G., and W. Walkinshaw (1946), Meteorological Factors in Radio Wave Propagation, 80 (Phys. Soc. of London).

Gallet, R. M., and W. F. Utlaut (1961), Phys. Rev. Letters **6,** 591.

Gopal Rao, M. S. V., and H. G. Booker (1963), J. Geophys. Res. **68,** 387.

MacDonald, G. F. J. (1961), J. Geophys. Res. **66,** 3639.

Smith, R. L. (1960), Guiding of whistlers in a homogeneous medium, J. Res. NBS **64D** (Radio Prop.), 505.

Smith, R. L. (1961), J. Geophys. Res. **66,** 3699.

Smith, R. L., R. A. Helliwell, and I. W. Yabroff, J. Geophys. Res. **65,** 815.

Yabroff, I. W. (1961), Computation of whistler ray paths, J. Res. NBS **65D** (Radio Prop.), No. 5, 485–505.

6. Whistlers

D. L. Carpenter

1. Field Operations

Field operations included continued synoptic recordings of whistlers, as well as an increasing number of relatively specialized studies. The two principal synoptic programs are the Whistlers-West network [Helliwell and Carpenter, 1961, 1962a], operated by Stanford University, and the Whistlers-East network [Laaspere, Morgan, and Johnson, 1962], operated by Dartmouth College.

A new VLF research facility has been installed on the research ship *Eltanin*. Under the direction of Stanford University, this new facility includes broad and narrow band receiving equipment, as well as a Rayspan real-time spectrum analyzer. The ship, a converted transport operated for the National Science Foundation by the U.S. Navy, began its activities in May 1962, and has operated extensively in the vicinity of South America and in Antarctic waters. New results include middle-latitude whistlers recorded at the geomagnetic equator, ionospheric noise triggered by a Navy VLF transmitter, and data on whistler occurrence rates over a wide range of latitudes.

The use of an island as a natural VLF transmitting antenna was suggested by Morgan [1960]. Deception Island, located near Antarctica in the South Shetlands at 60.5°W, 63°S (geographic), was found to be an attractive possibility, both because of its location in a region of high whistler activity and because its configuration approximates that of a half-wave slot resonant near 5 kc/s. An experimental program to determine feasibility of operating such an antenna has been initiated.

N. Brice conducted an airlifted VLF survey in the Antarctic along a route extending from the base of the Palmer peninsula to the dip pole. The principal objective was to study geomagnetic control of VLF emission activity. Well-defined, high-latitude whistler traces were recorded in December 1961 near the present Eights station (75.2°S, 77.2°W geographic), thus suggesting the possibility of useful high-latitude whistler observations in the Antarctic during the austral summer (private communication).

The Stanford group has recently experimented with mobile recording units installed on trailers loaned by the U.S. Navy. These units have been used for whistler-mode recordings and for field-strength studies of the direct signal from Navy transmitters. The equipment has been found adaptable to many specialized purposes, including spaced-station studies for comparison with data recorded at fixed sites, direction finding by means of switching between east-west and north-south loops, and operation at the northern hemisphere conjugate of various stations in the southern hemisphere.

Generally speaking, the trend in field operations is toward broader frequency range, improvided calibration and control of equipment, more extensive data reduction in the field, and greater flexibility of schedules for the fulfillment of special needs, such as for continuous recordings during a magnetic storm.

2. Methods of Spectrum Analysis

A significant advance in the area of spectrum analysis was the adaptation of the "Rayspan" filter unit to the routine production of spectrograms in real time [Helliwell et al., 1961]. The new system, incorporating commercially-available components, employs a camera and oscilloscope and provides a variety of time and frequency scales. Prior to the development of this device, it was necessary to employ a relatively slow method using the well-known Sonagraph. With the new technique, records can be produced at 300 times the speed of the Sonagraph. As a result it has been possible greatly to increase the rate of production of useful whistler and VLF emission data.

3. Methods of Scaling Whistlers

A new method of scaling frequency and traveltime at the whistler nose, (f_n, t_n), was developed by Smith and Carpenter [1961]. The method is essentially an extrapolation technique, and was found to be of particular value in the case of middle-latitude whistlers whose observable range of frequencies does not extend above some fraction of the nose frequency. The new method increased by at least an order of magnitude the number of middle-latitude whistlers from which information on electron density as a function of position in the magnetosphere can be derived. (From whistler theory it is known that the value of nose frequency for a whistler trace defines the approximate whistler path latitude, and that traveltime at the nose is proportional to the integral of the square root of the electron density along the path.)

Experimental error in scaling (f_n, t_n) was investigated by Carpenter [1962a]. It was found that the extrapolation method provides information on electron-density level and on geocentric distance at the top of the path that is comparable in accuracy with the information obtained from direct observation of nose trace. For (f_n, t_n) studies, it was found that the error in measuring whistler traveltime is usually somewhat less than 1 percent. On this basis, and for either directly scaled or extrapolated values of (f_n, t_n), the 50-percent scaling error in geocentric distance at the top of the path was found to be $\pm 0.15\ R_E$ in a typical case. The corresponding error in relative electron-density level was found to be ± 8 percent.

4. Electron Density Studies

The electron-density profile in the magnetosphere was investigated by Pope [1961, 1962]. He analyzed several nose whistlers recorded at College, Alaska, on March 19, 1959. The traces scaled were found to represent paths extending from about 4 to 5.5 earth radii (geocentric distance) in the geomagnetic equatorial plane. It was found that the data were most consistent with an electron-density model proposed earlier by Johnson [1959], and it was concluded that the density profile derived from the data could be expressed as

$$N = (2580/R^3) \exp (3.03/R)$$

where N is the number density of electrons/cm^3 and R is the distance from the earth's center in earth radii.

Carpenter [1962b] studied some of the variations in electron density with time along paths extending to 2 to 4 earth radii in the geomagnetic equatorial plane. He used (f_n, t_n) data from whistlers recorded primarily at Stanford, (43.7° N, 298.4° E geomagnetic) and Seattle (53.6° N, 294.4° E geomagnetic). It was found that the solar-cycle variation is small, amounting to a reduction from early 1958 to early 1961 by about 20 to 25 percent. On this basis it was estimated that, at the forthcoming minimum of the sunspot cycle, the 12-month average density will be reduced from 1958 levels by about 30 to 40 percent. This is a much smaller reduction than is observed at the maximum of the F region. Evidence was found that the solar-cycle variation is most pronounced when examined near the December solstice, and that the variation from year to year near the June solstice is relatively small.

The annual variation [Smith, 1960; Helliwell, 1961] is known to exhibit a maximum near the December solstice and a minimum near the June solstice. Carpenter [1962b] extended the earlier studies, and found that the annual variation is a persistent phenomenon, with an amplitude that diminishes with decreasing solar activity. In 1958 the average June density level was reduced by about 35 percent from the January value, while in 1961 the corresponding figure was about 20 percent.

The explanation of the annual variation has not yet been found. Carpenter inferred from his investigations that the amplitude and phase of the variation do not vary substantially with longitude. If this is in fact so, the variation probably cannot be explained on the basis of localized effects, such as the annual variation in geomagnetic latitude of the subsolar point at a particular geomagnetic longitude. Helliwell [1961] pointed out that if this geomagnetic asymmetry is the controlling factor, then the annual variation in electron density should reverse in phase in the eastern hemisphere of the earth.

Magnetic storm effects were investigated by Carpenter [1962a, b, c]. Using the new extrapolation technique of scaling (f_n, t_n), he found that traveltime at the whistler nose often decreased during the 72-hr period following a 3-hr K_p value of 6 or greater. It was concluded from the analysis that, in the geocentric range 2 to 4 earth radii, electron-density levels are often depressed by 15 to 20 percent during the later phases of a magnetic storm. During some severe storms, levels may be depressed by as much as a factor of 10.

A new phenomenon reported by Carpenter [1963a] is the presence of a "knee" in the equatorial profile of magnetospheric ionization. At some point in the profile the electron density drops rapidly until it reaches a level that may be reduced by a factor of about 6 from the normal level. It was suggested that the knee exists at all times, and that it moves inward with increasing magnetic activity. During periods preceded within 72 hr by severe magnetic storms, the position of the knee tends to fall between about 2.5 and 3.5 R_E (geocentric distance in the geomagnetic equatorial plane). The corresponding range for moderately disturbed conditions is about 3 to 4.5 R_E. It was found that knee whistlers account for a substantial number of observations of deep density depressions during magnetically disturbed periods.

The Dartmouth workers studied magnetospheric density variation by means of whistler observations begun in 1957 at Port Lockroy (53.4°S, 3.9°E geomagnetic) [Gomez, Morgan, and Laaspere, 1962]. Whistler dispersion was scaled at frequencies below 5 kc/s. For the month of June 1958, it was found that dispersion falls some 10 percent during the afternoon and evening to a minimum value at 0100 local time, and this value is then maintained until 0500. Data for September 1958 supported the existence of a stable dispersion value between 0200 and 0400 local time. Data from this restricted range of hours were then used to obtain monthly dispersion values representing the periods November 1957 to October 1958 and November 1960 to October 1961. A large annual variation was found in both years, with the same phase as that found for the Whistlers-West network by Smith [1960] and Helliwell [1961]. The relative magnitude of the variation was approximately the same as that observed at Stanford [Carpenter, 1962b]. Thus, the Port Lockroy results provided independent evidence that the annual variation is a worldwide effect.

The Dartmouth investigation also confirmed that the principal solar-cycle variation in whistler dispersion takes place near the December solstice Over the 3-yr interval from 1957–58 to 1960–61, relatively little change in whistler dispersion at the June–July minimum was found. It was pointed out that, in contrast to this pattern, the air density deduced from satellite drag shows a secular change which is approximately the same throughout the year.

5. Propagation of Whistlers

Properties of the Source

A strong whistler excited by the high-altitude (400 km) nuclear explosion Starfish Prime was studied by Helliwell and Carpenter [1962b]. (See also Allcock et al., [1963].) The upper cutoff frequency of the shot whistler was found to be about 32 kc/s, as compared to about 10 kc/s for a strong natural whistler traveling prior to shot time in the same magnetospheric paths. The difference in the upper cutoff frequencies of these whistlers was attributed to corresponding differences in the amplitude spectra of their respective sources.

Spectrum analysis of the impulse which propagated in the earth-ionosphere waveguide from the Starfish Prime shot at Johnston Island to Wellington, New Zealand revealed no dispersion other than that attributable to the earth-ionosphere waveguide. It was concluded that the electromagnetic impulse produced by the explosion was created below the ionosphere, and not at the 400 km altitude of the shot.

Propagation in the Earth-Ionosphere Waveguide

A study of propagation in the earth-ionosphere waveguide at VLF was made by Crary [1961]. The work was based on a sharp-boundary model of the ionosphere and included a ray-theory calculation of the intensity, polarization, and direction of arrival of VLF waves originating in the ionosphere and received on the ground. In this study it was discovered that the apparent polarization of a received whistler could in fact be reversed in the earth-ionosphere waveguide because of the anisotropy of the ionosphere. This result led to an explanation of previously puzzling polarization measurements of whistlers. Experimental studies of the direction of arrival and polarization of whistlers had indicated that, although the whistler polarization was often circular and of the right sense, it was frequently linear and even of reverse sense. The new theory offered a plausible explanation for this anomaly. Crary also computed the variation of field strength along the ground for a wave generated in the ionosphere. For a 5-kc/s wave, and for summer-night ionospheric conditions over sea water, his results may very roughly be approximated by assuming a rate of loss of 13 db per 1000 km in the first 3000 km, and 3 db per 1000 km in the region 3000 to 12000 km from the subexit point. In connection with these same studies, efforts were made to determine experimentally the direction of arrival of whistlers. A goniometer system with "sense" was developed and applied to a number of whistlers. Although the results were consistent with the basic theory of whistlers, they were not considered conclusive because of the large errors inherent in the technique.

Coupling Theory

Certain aspects of the coupling of whistlers between the earth-ionosphere waveguide and the ionosphere were investigated theoretically by Helliwell [1962a]. He considered the conditions under which whistlers would cross the boundary and be trapped in a given field-alined column of ionization, and secondly, the problem of the exit of the whistler from such a column. This first-order coupling theory showed that coupling into and out of whistler ducts was most favorable when the transmitter (or receiver) was located on the high-latitude side of the whistler duct. Experimental confirmation of this theory was found in synoptic whistler data from different latitudes.

Discrete Path Theory

The whistlers excited by five nuclear explosions were studied by Helliwell and Carpenter [1962b]. It was found that the observed frequency-versus-time curve of the whistlers is determined by the location and properties of the path, and not the location of the source or receiver. Transequatorial excitation of whistler paths was found to occur, lending support to the concept of the hybrid whistler [Helliwell, 1959].

The propagation characteristics of whistlers trapped in field-alined columns of enhanced ionization were investigated by Smith [1961a]. The experimental whistler evidence for the existence of such columns or ducts was discussed. Calculations of the average group-ray velocity of a trapped whistler were made, and it was found that the propagation velocity may be closely approximated by assuming that the energy travels along the ionization maximum, with the wave normals alined with the magnetic field. A cutoff frequency of approximately one-half the minimum gyrofrequency was predicted for whistlers propagating in ducts.

Dispersion Theory

The frequency-versus-time curve of whistlers propagating on field-alined paths was investigated theoretically by Smith [1960, 1961b]. It was found that when the dispersion curve is normalized to the nose frequency and traveltime at the nose, the shape of the curve is only weakly dependent upon both the choice of a model of ionization distribution and upon the path latitude.

Absorption in the Ionosphere

Absorption losses within the ionosphere were computed by Helliwell and Dunckel [1963]. For whistler frequencies, they made the assumptions that the effects of ions are negligible, that the quasi-longitudinal approximation [Ratcliffe, 1959] is valid, and, drawing on the work of Altman and Cory [1962a, b], that reflections are insignificant. The absorption rate was then shown to be greatest in the D region, where the major source of loss is electron-neutral collisions. In addition, a minor absorption peak in the F region was found to occur as a result of electron-ion collisions. The total absorption integrated through the region 60 to 200 km in altitude was found to be about 10 db for noon and about 2 db for midnight at 55° geomagnetic latitude. Under polar blackout conditions the absorption increased to 44 db. (The values must be doubled for two passages through the lower ionosphere.)

These figures were then used to explain the large diurnal variation of whistler occurrence noted at middle latitudes, as well as the total disappearance of VLF signals during polar blackouts.

Landau Damping of Whistlers

Scarf [1962] investigated the thermal damping of whistlers using the small amplitude solutions to the coupled Boltzmann-Maxwell equations. It was found that the damping is associated with cyclotron resonance for a fraction of the electrons in the magnetosphere, and that the resultant attenuation provides a sharp cutoff at 0.5 to 0.7 of the minimum cyclotron frequency along the path. The correlation of whistler data with the derived complex dispersion relation was used to evaluate electron temperatures at several earth radii; a specific numerical example gave $T \simeq 10^5$ °K at $R=4\ R_E$ (geocentric). The thermal analysis was applied by Liemohn and Scarf [1962a] to data supplied by Pope, and the most reasonable results for the effective density and temperature at $R/R_E \simeq (4\text{–}4.5)$ appeared to be $N \simeq (200\text{–}700)$ electrons/cm^3 and $T \simeq 2.5 \times 10^5$ °K. In another paper, Liemohn and Scarf [1962b] examined the thermal attenuation of whistlers, assuming, for simplicity of analysis, that the electron component has a velocity distribution of the (Cauchy) form $\sim (v^2+a^2)^{-3}$, which corresponds to an energy dependence of $E^{-2.5}$ when $|v| >> a$ (a being the rms velocity). It was pointed out that the exact shape of the distribution and the concept of temperature are only relevant in the sense that they give the fraction of the electrons that participate in the damping interaction at the Doppler-shifted phase velocity. For a total density of 200 electrons/cm^3 at $R \simeq 4\ R_E$, the thermal attenuation mechanism was found to predict an electron flux of $\sim 4 \times 10^5$ electrons/cm^2 sec ev for energies near 250 ev.

Occurrence of Whistlers

Whistler occurrence data covering five years of observations in the Whistlers-East network and at a number of other stations were analyzed statistically by Laaspere, Morgan, and Johnson [1962]. It was found that most diurnal whistler curves can be considered to be variations of one basic form which shows three peaks superimposed on a broad nighttime maximum. These peaks are located at about 2000, 2400, and 0400 hr local time. Some stations may also show high activity in local summer at about 1800 or 0600 hr.

The shape of the diurnal curves of whistler activity was found to be closely connected with the local season at the point of observation. The diurnal variation of thunderstorm activity was found to be of minor importance in determining the shape of the whistler curve. It was concluded that propagation effects of whistler-mode signals, including absorption in the D region, probably determine both the main shape and much of the detail of the diurnal whistler curves.

Whistler Propagation in the Remote Magnetosphere

Extensive spectral analysis of records from Byrd Station in the Antarctic (70.5° S geomagnetic) revealed that whistlers frequently propagate along paths with minimum gyrofrequency ranging as low as 60 gamma [Carpenter, 1963b]. (For an undistorted dipole field, this lower limit corresponds to $R \simeq 8\ R_E$, where R is geocentric distance in earth radii in the geomagnetic equatorial plane.) It was found that for observations at Byrd during the June–August period, high latitude whistlers are more frequently observed when the field lines terminating near Byrd are on the sunlit side of the earth. It was concluded that the new data can be used to extend present studies of electron density to greater heights, and to support a new line of investigation of geomagnetism in the remote magnetosphere.

Characteristics of Whistler Spectra

An atlas of whistlers and VLF emissions and a survey of VLF spectra from Boulder, Colo. were prepared by Jones et al., [1963]. The work included samples of whistlers, examples of interactions between whistlers and emissions, illustrations of whistler and emmission activity during magnetically disturbed periods, and a synoptic survey of the period March through June 1957.

6. Fixed-Frequency Experiments

Whistler-mode echoes from U.S. Navy fixed-frequency transmitters operating in the range from 14.7 kc/s (NAA) to 22.3 kc/s (NSS) have been under investigation for several years. In 1959 the Stanford group inaugurated a program of narrowband observations at stations in North America, South America, New Zealand, and the Antarctic, based on programmed transmissions from NPG, NSS, NPM, and NAA. Among the reported results [Helliwell, Katsufrakis, and Carpenter, 1962] are the following:

a. The whistler-mode echoes from pulse transmissions may be associated with a single path, or with several paths. They may be shorter or longer in duration than the transmitted pulse. Individual echoes may show large variation in amplitude as well as deep fading over a series of pulse periods.

b. The day-to-night and seasonal variations in echo activity are explained mainly in terms of absorption of the wave as it passes through the lower ionosphere. Systematic variations of activity during the hours of darkness are thought to be related to ducting and F-region ionization gradients.

c. From the diurnal and seasonal variations of echo activity, it is concluded that whistler-mode signals reach high-latitude stations, such as Byrd, by traveling in the earth-ionosphere waveguide after exiting at middle latitudes.

d. From echo activity data it is deduced that the two-hop echoes studied in the experiment must have passed through the D region at both ends of the path.

e. Day-to-day whistler-mode activity varies widely, suggesting that activity is controlled either by the trapping ability of the magnetospheric ducts or by the horizontal gradients of ionization in the *F* region.

f. Frequent absence of whistlers when fixed-frequency activity is high confirms the expectation that the day-to-day variation in whistler rate is affected significantly by thunderstorm activity.

g. The observation of whistlers when no fixed-frequency echoes are observed suggests the presence of a variable high-frequency cutoff in whistler-mode propagation.

h. Periodic deep fading of whistler-mode echoes shows periods in the range of 20 to 60 sec. The fading is attributed to beating between two echoes of comparable intensity and of nearly the same group delay. Systematic variations in the relative electron content along the two paths are suggested as the cause.

i. Group delays are closely related to the geomagnetic latitude of the receiving station, with the higher-latitude stations observing the higher average delays. However, stations at high latitudes often observe low-latitude paths, whereas low-latitude stations seldom observe high-latitude paths. This is interpreted to mean that, after injection into the earth-ionosphere waveguide, the whistler-mode echoes travel mainly in the direction of the geomagnetic pole. It is concluded that, for best whistler-mode transmission, the receiver and transmitter should be located on the high-latitude sides of the magnetospheric duct.

j. Group delays are reduced during magnetic storms and are lower in June than in December, which is in accord with whistler data.

k. The correlation of group delay as well as echo occurrence at spaced stations is generally poor except when the stations are closely spaced, or when one station is close to the conjugate point of the other.

A study of two-hop echoes from station NPG (18.6 kc/s, located near Seattle, Washington) was made by Willard [1961, 1962]. He found a peak in echo activity in the early morning hours and a secondary peak in the evening. It was found that successive echoes can vary substantially in strength and that individual echoes can contain large amplitude fluctuations. Interference between paths with slightly different delay times was advanced as a possible explanation of these variations. It was also observed that a VLF transmitter may excite whistler ducts some distance from its antenna. Willard made a two-station study at Seattle, Wash., and at Ashland, Oreg. (about 500 km south of Seattle), and found that the stronger echoes are usually heard at both stations. The delay and time-of-occurrence statistics were somewhat similar, but the higher latitude station received a significant number of short delays as well as an expected number of longer delays.

An FM experiment using NPG was initiated by the Stanford group. The purpose of the experiment was to increase the sensitivity of controlled whistler-mode propagation studies, and in particular to provide for improved discrimination between separate whistler-mode paths. The NPG transmitter, nominally at 18.60 kc/s, was swept linearly over a 2-sec interval from 18.65 kc/s to 18.55 kc/s. As a result of whistler-mode echoing, the received signal was expected to contain several discrete difference-frequency components in the several-c/s range, corresponding to one or more whistler-mode paths. The experiment produced positive results, which will be reported in detail at a later date.

7. Satellite Studies

Vanguard III

The Vanguard III satellite (1959 Eta) used the sensing coil of a proton precession magnetometer to detect the first whistlers observed at ionospheric heights. A preliminary examination of about 100 of a total of 4,000 magnetometer transmissions was reported by a NASA group at the Goddard Space Flight Center, Greenbelt, Md. [Cain et al., 1961]. A preliminary analysis was given for about 100 whistlers observed between September 18 and December 12, 1959, at low latitudes over the altitude range 510 to 3750 km. About 90 percent of the whistlers were observed between 6 p.m. and 6 a.m. local time, indicating that absorption by the ionosphere was low at night. The intensity of the *H* component of the whistlers was estimated to lie mostly between 0.01 and 0.5 gamma, occasionally exceeding 1 gamma. It was found that 60 percent of the whistlers examined occurred during 25 days of magnetic disturbance (out of a total of 85 days). From the occurrence statistics it was inferred that the ionization becomes more field-alined during a magnetic disturbance.

Lofti I

Lofti I (1961 Eta) was a Navy satellite designed to study VLF radio penetration of the ionosphere at 18.0 kc/s. It was launched into a roughly equatorial orbit on February 21, 1961, and functioned for 36 days. The orbit was elliptical with an apogee of 960 km and perigee of 166 km. A launch-sequence malfunction restricted and modified the planned experiment, but the magnetic loop receiving system was fully operable.

Interim results on the Lofti I experiment were reported by a group at the U.S. Naval Research Laboratory in Washington, D.C. [Leiphart et al. 1962]. Strong signals were received in the ionosphere from 18-kc/s transmitters NBA (Panama) and NPG (Seattle, Washington). The signals were attenuated less at night and were observed as far away as Australia, 16,000 km from the transmitter. The data (not yet complete) on signal intensity of 18-kc/s pulses from NBA indicated that 50 percent of the time the magnetic field intensity of the VLF wave is reduced less than 13 db at night and less than 38 db by day because of passage through the ionosphere. These results apply to signals received by the satellite at latitudes less than 28°N (geographic) and to the north of the transmitter. The data which had been examined did not disagree with the concept that the absorption loss occurs almost entirely in the *D* region. Limited data representing simultaneous operation at 18 kc/s of NPG and NBA indicated that the NPG signal in the daytime ionosphere was attenuated relative to its computed ground-signal intensity roughly 10 db less than NBA's signal. This comparison afforded some experimental confirmation of the effect on attenuation of difference in the angle of the wave normal relative to the geomagnetic field (see also Rorden, Helliwell, and Smith [1962]).

The observed time delays of the 18-kc/s signals ranged from 10 to 200 msec. Whistler-mode echoes were observed as much as 1.3 sec after the directly received pulses.

Rorden, Helliwell, and Smith [1962] studied some aspects of the Lofti I data. Because there was continuous reception of signals over long distances, it was concluded that propagation was not limited to the discrete paths or ducts to which ground-based whistler observations may be confined. The "non-ducted" mode was used to help explain an interesting observation in the satellite, namely, that the echo was sometimes stronger than the first "direct" signal observed.

Alouette

The Canadian workers at DRTE included a broadband VLF experiment in their highly successful topside-sounding satellite, the Alouette (see [Warren, 1962]). Alouette was launched by NASA into a nearly circular polar orbit (altitude about 1000 km) on September 29, 1962. The output of its 1 to 10 kc/s VLF receiving system modulates a carrier for direct readout by ground stations. The Dartmouth and Stanford groups are cooperating with the Canadians to obtain simultaneous whistler recordings on the ground and in the satellite.

8. Artificially Stimulated Ionospheric Noise

Helliwell [1962b] found that ionospheric noise can be artificially stimulated by a VLF transmitter. IGY records showed VLF emissions of the "riser" type being triggered repeatedly by Morse code signals from station NPG (Jim Creek, Wash.) on 18.6 kc/s. The triggered risers were identified on a routine two-minute synoptic whistler recording taken at Wellington, New Zealand, during a magnetic disturbance. (More recently, similar noises triggered by NAA have been found on recordings aboard the ship *Eltanin.*)

Each riser lasted about 0.1 sec and was initiated shortly after the beginning of a whistler-mode echo from NPG. In nearly every one of the approximately 200 cases found on the record, the riser began at the frequency of the transmitter (18.6 kc/s) and terminated at a frequency which varied between 20 kc/s and 30 kc/s. Risers were associated with 6 percent of the dots and 97 percent of the dashes, indicating that the probability of triggering increases with the duration of the exciting wave.

The artificially triggered risers were found to be similar in many respects to naturally occurring risers, which are sometimes triggered by whistlers and which are more commonly observed at lower frequencies (1 to 10 kc/s). The new results showed for the first time that risers can be triggered by fixed-frequency signals as well as by whistlers. They also showed that the conditions for generation must exist more or less continuously over periods of several minutes at least. Thus, the conclusion was reached that it is not necessary to postulate the prior existence of discrete bunches of charged particles to explain the generation of discrete VLF noise forms. Instead, it appears that the passing wave and the plasma interact in such a way as to create the conditions necessary for the radiation of short bursts of noise.

References

Allcock, G. McK., R. A. Helliwell, O. K. Branigan, and J. C. Mountjoy (1963), Whistler and other VLF phenomena associated with the high-altitude nuclear explosion on July 9, 1962 (in press).

Altman, C., and H. Cory (1962a), The transmission of audio-frequency electromagnetic waves through the terrestrial ionosphere in the magneto-ionic mode, J. Geophys. Res. **67,** No. 10, 4086–4090.

Altman, C., and H. Cory (1962b), Absorption of audio-frequency electromagnetic waves traversing the ionosphere in the magneto-ionic mode, Bull. Res. Counc. Israel **11c,** 1–18.

Cain, J. C., I. R. Shapiro, J. D. Stolarik, and J. P. Heppner (1961), A note on whistlers observed above the ionosphere, J. Geophys. Res. **66,** No. 9, 2677–2680.

Carpenter, D. L. (April 1962a), The magnetosphere during magnetic storms; a whistler analysis, Stanford Electronics Labs. Rept. 62–059, Stanford Univ.

Carpenter, D. L. (1962b), Electron-density variations in the megnetosphere deduced from whistler data, J. Geophys. Res. **67,** No. 9, 3345–3360.

Carpenter, D. L. (1962c), New experimental evidence of the effect of magnetic storms on the magnetosphere, J. Geophys. Res. **67,** No. 1, 135–145.

Carpenter, D. L. (Mar. 15, 1963a), Whistler evidence of a "knee" in the magnetospheric ionization density profile, J. Geophys. Res. **68,** No. 6.

Carpenter, D. L. (1963b), Extension of whistler studies to the remote magnetosphere (in preparation).

Carpenter, D. L., and G. B. Carpenter (Jan. 1962), Data summary: whistler-mode propagation, Stanford Electronics Labs. Rept. 62–001, Stanford Univ.

Crary, J. H. (July 1961), The effect of the earth-ionosphere waveguide on whistlers, Stanford Electronics Labs. Tech. Rept. 9, Contract AF18(603)–126, Stanford Univ.

Gomez, P. D., M. G. Morgan, and T. Laaspere (1962), The diurnal and long-term variations of whistler dispersion (in preparation).

Helliwell, R. A. (1959), Whistler paths and electron densities in the outer ionosphere, Proc. Symposium on Physical Processes in the Sun-Earth Environment, DRTE Pub. 1025, 165–175, July 1959.

Helliwell, R. A. (1961), Exospheric electron density variations deduced from whistlers, Ann. Geophys. **17,** No. 1, 76–81.

Helliwell, R. A. (1962a), Coupling between the ionosphere and the earth-ionosphere waveguide at very low frequencies (in press).

Helliwell, R. A. (Oct. 1962b), Artificially stimulated VLF electromagnetic radiation from the earth's atmosphere, presented at URSI-IRE Meeting, Ottawa, October 1962.

Helliwell, R. A., and D. L. Carpenter (Mar. 1961), Whistler-West IGY-IGC synoptic program, Stanford Electronics Labs. Final Rept., NSF Grant IGY 610./20 and G-8839, Stanford Univ.
Helliwell, R. A., and D. L. Carpenter (1962a), Whistlers-West results from the IGY-IGC-59 synoptic program, IGY Bull., NAS (57) 1–9; Trans. AGU **43,** No. 1, 125–133.
Helliwell, R. A., and D. L. Carpenter (1962b), Whistlers excited by nuclear explosions, presented at URSI-IRE Meeting, Ottawa, October 1962.
Helliwell, R. A., J. H. Crary, J. P. Katsufrakis, and M. L. Trimpi (Nov. 1961), The Stanford University real-time spectrum analyzer, Stanford Electronics Labs. Tech. Rept. 10, Contract AF18(603)-126, Stanford Univ.
Helliwell, R. A., and N. Dunckel (1963), Absorption of the whistler-mode caused by collisional damping (in preparation).
Helliwell, R. A., J. Katsufrakis, and G. Carpenter (Mar. 1962), Whistler-mode propagation studies using Navy VLF transmitters, Stanford Electronics Labs. Rept. 62-035, Stanford Univ.
Johnson, F. S. (April 1959), The structure of the outer atmosphere including the ion distribution above the F_2 maximum, Tech. Rept. LMSD-49719, Lockheed Missiles and Space Div., Sunnyvale, Calif.
Jones, D. L., R. M. Gallet, J. M. Watts, and D. N. Frazer (Jan. 1963), An atlas of whistlers and VLF emissions, NBS Tech. Note 166.
Laaspere, T., M. G. Morgan, and W. C. Johnson (1962), Some results of five years of whistler observations from Labrador to Antarctica (to be published in Proc. IRE).
Leiphart, J. P., R. W. Zeek, L. S. Bearce, and E. Toth (1962) Penetration of the ionosphere by very-low frequency radio signals—interim results of the Lofti I experiment, Proc. IRE **50,** No. 1, 6–17.
Liemohn, H. B., and F. L. Scarf (1962a), Exospheric electron temperatures from nose whistler attenuation, J. Geophys Res. **67,** No. 5, 1785–1789.
Liemohn, H. B., and F. L. Scarf (1962b), Whistler attenuation by electrons with an $E^{-2.5}$ distribution, J. Geophys. Res. **67,** No. 11, 4163–4167.
Morgan, M. G. (1960), An island as a natural very-low-frequency transmitting antenna, IRE Trans., Antennas Propagation **AP-8,** No. 5, 528–530.
Pope, J. H. (1961), An estimate of electron densities in the exosphere by means of nose whistlers, J. Geophys. Res. **66,** No. 1, 67–75.
Pope, J. H. (1962), A correction to the exospheric electron density estimate using the nose whistlers of Mar. 19, 1959, J. Geophys. Res. **67,** No. 1, 412.
Ratcliffe, J. A. (1959), The Magneto-Ionic Theory and Its Application to the Ionosphere (Cambridge Univ. Press, Cambridge, England).
Rorden, L. H., R. A. Helliwell, and R. L. Smith (Sept. 1962), An interpretation of Lofti-I VLF observations, paper presented at AGARD Meeting, Munich, Germany, Sept. 1962.
Scarf, F. L. (1962), Landau damping and the attenuation of whistlers, Phys. Fluids **5,** No. 1, 6–13.
Smith, R. L. (July 1960), The use of nose whistlers in the study of the outer ionosphere, Stanford Electronics Labs. Tech. Rept. 6, Contract AF18(603)-126, Stanford Univ.
Smith, R. L. (1961a), Propagation characteristics of whistlers trapped in field-aligned columns of enhanced ionization, J. Geophys. Res. **66,** No. 11, 3699–3707.
Smith, R. L. (1961b), Properties of the outer ionosphere deduced from nose whistlers, J. Geophys. Res. **66,** No. 11, 3709–3716.
Smith, R. L., and D. L. Carpenter (1961), Extension of nose whistler analysis, J. Geophys. Res. **66,** No. 8, 2582–2586.
Warren, E. S. (1962), Sweep-frequency radio soundings of the top side of the ionosphere, Can. J. Phys. **40,** No. 11, 1692–1694.
Willard, H. R. (1961), Two-hop 18.6 kc whistler-mode echoes received at Seattle, J. Geophys. Res. **66,** No. 6, 1976–1977.
Willard, H. R. (1962), Characteristics of whistler-mode echoes based on two-station observations, presented at AGU Western National Meeting, Stanford University.

7. Summary of Research on VLF and ELF Emissions

Roger M. Gallet

1. The VLF Emissions—Their Relations With Whistlers and High Energy Particle Phenomena

The VLF emissions, originating in the magnetosphere and the upper ionosphere, are of particular interest because of their intimate relation to whistlers and to high-energy particle phenomena in the magnetosphere. These two fields are reviewed in the reports immediately preceding and following the present synopsis. It is now well understood that VLF emissions propagate in the whistler mode, and that they are produced by bunches or streams of high energy particles moving along lines of force in the magnetosphere. In nature and energy these particles are not different from the Van Allen belt particles or from the intense fluxes of high energy electrons precipitating upon the upper atmosphere that are observed by high altitude balloons. The source of VLF emissions was interpreted, and they were systematically studied in several U.S. laboratories prior to the discovery of these two classes of phenomena (early 1958 for the geomagnetically trapped radiation, and mid 1957 for the precipitation phenomena). A first review of the properties of VLF emissions, and the basic mechanism of their production, was presented by the author at the XIIth URSI General Assembly held in Boulder, Colo., September 1957.

It took some time to recognize that these natural radio phenomena and the more or less direct detection of trapped or precipitating particles were different aspects of the same general class of geophysical phenomena. This was partly due to the unavoidable specialization of scientists: cosmic-ray physicists and radio physicists generally have very little common meeting ground. But, and more significant from a physical point of view, the relationship between the two fields of observations is far from being obvious, and is obscured by many secondary effects, such as the strong variations of the ionospheric absorption for VLF radio signals, and the lack of continuous observations of the particle fluxes at the same place. The more or less steady Van Allen belt, as pictured from the satellite observations, does not produce an observable background of continuous VLF emissions, even if the velocity of the individual

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particles is, from the present theory of the emission mechanisms, largely sufficient to produce the radio emission. The VLF emissions are essentially transient, over a wide range of time scales, and their intensity can be very large compared to the threshold of detectability (typically 10^{-15} to 10^{-14} m^{-2} $(c/s)^{-1}$ compared to 10^{-18} or 10^{-19}). It follows that VLF emissions are more closely associated with *transient* particle activity in the magnetosphere superposed on the more permanent background revealed by satellites. In addition, the observed VLF emissions (sharp and strong discrete events and hiss, well characterized by their spectra) are not produced by individual particles but are due to the *collective effect* of excess density particles in bunches or streams.

From the present state of the theory, as well as from the observed periods of certain periodic emissions (the VLF pulsations; see sec. IV), one can deduce that, for a large majority of the VLF emissions, the velocities of charged particles required for producing the emissions correspond to electron energies of the order of few kilovolts. The recent counter results obtained with the Injun I satellite, equipped to record electrons with energies as low as 1 kev and on a very short time scale, show very large and rapid fluctuations of the particle fluxes, and are in much better agreement with the deductions made from the VLF emission observations than were the earliest measurements.

To facilitate such a comparison the reader is referred to the following report by J. R. Winckler, and to the following survey papers:

Van Allen, J. A., (1962), Dynamics, composition and origin of the geomagnetically-trapped corpuscular radiation, Proc. XIth General Assembly of the International Astronomical Union, 1961, **XI B,** 99–136.

Surveys concerning the precipitation of transient fluxes of high energy electrons:

Winckler, J. R., (1962), Atmospheric phenomena, energetic electrons, and the geomagnetic field, J. Res. NBS **66D** (Radio Prop.), 127–143.

Kellog, P. J., (1963), Auroral X-rays, electron bombardment and trapped radiation, Planet. Space Sci. **10,** 165–178.

Concerning intense fluctuations of low energy electrons observed with Injun I:

O'Brien, B. J., and C. D. Laughlin, (1962), An extremely intense electron flux at 100 kilometer altitude in the auroral zone, J. Geophys. Res. **67,** 2667–2672.

O'Brien, B. J., C. D. Laughlin, J. A. Van Allen, and L. A Frank, (1962), Measurements of the intensity and spectrum of electrons at 1000 kilometer altitude and high latitudes, J. Geophys. Res. **67,** 1209–1225.

At the present time it has become clear that VLF emissions are closely related to the *dynamics* of high energy particle phenomena in the magnetosphere. Unlike whistlers, which are an important *propagation* phenomenon, VLF emissions are characterized by an *emission process,* producing well-defined narrow bands of frequency due to the passage of a relatively few high velocity particles through the ambient plasma. When they are emitted, the electromagnetic waves propagate like whistlers. To understand the shape of the dynamic spectra of VLF emissions it is necessary to take into account the results available from whistler studies of the structure of the magnetosphere. The reader is referred to the preceding report by D. L. Carpenter.

2. Trends in the Field of VLF and ELF Emissions Since 1960

One may characterize the period since the last URSI General Assembly (London, September 1960) by the following general statements:

a. The separation between the studies of whistler and VLF phenomena became clearer and better accepted.

b. The study of VLF emissions is no longer pursued by itself, and there is a deliberate search for the relationship with high energy particle phenomena. *Vice versa,* particle physicists are now well aware of the importance of this aspect in their studies.

c. It has become evident that there is an important relationship between ELF observations and VLF emissions, and that the customary separation was mainly artificial. It has been realized that at least one fraction of the geomagnetic micropulsations have very definite spectra, exhibiting well-defined frequencies slowly varying with time, and very much alike VLF emissions. Also, at least a fraction of these geomagnetic micropulsations propagates as progressive *hydromagnetic waves* through the magnetosphere, or is standing ELF oscillations of parts of the magnetosphere (such as a particular bundle of lines of force). The detailed mechanism of the production of these hydromagnetic waves is still quite a puzzle, but they are related to the interaction of solar plasmas with the magnetosphere. It is possible that some well-defined ELF frequencies are produced by streams or bunches of particles in a way similar for hydromagnetic waves to the traveling wave tube mechanism producing VLF emissions. The term *Hydromagnetic Emissions* has been very appropriately used by Tepley [1961].

3. Morphological and Statistical Studies

Since a separate report on the field of VLF emissions was not yet prepared for previous URSI General Assemblies, it is perhaps useful to give a general perspective of the development.

Systematic studies of VLF emissions, concerning their classification, shapes, rate of occurrence, etc . . . started early in 1956 at several U.S. laboratories. The basic mechanism of their production by particles moving along lines of force in the exosphere was understood at the beginning of 1957 and first calculations of predicted shapes of dynamic spectra, by means of electronic calculators, were made at the same period. The results presented at the XIIth General Assembly, covering the period 1957–1960 [Helliwell and Morgan, 1960] were mainly concerned with many IGY results, and in particular variation in occurrence for different types, area of reception of a given VLF emission, and in general with results of a *statistical* significance. Only one attempt at association with other geophysical phenomena was reported, the relation established between auroras, VLF hiss, and chorus [Martin, Helliwell, and Marks, 1960].

Further surveys of a *statistical* nature have been published during the period covered in this report [Helliwell and Carpenter, 1962; Laaspere, Morgan, and Johnson, 1962; Pope, 1963]. They confirm and extend the results already reported in 1960 [Helliwell and Morgan, 1960]. One could now consider that the main statistical and synoptic properties are quite well established; perhaps only the variation of VLF emission occurrence as a function of solar activity still remains to be determined.

Most of the spectral shapes of VLF emissions are now well known observationally; an atlas of the most common forms has been published [Jones, Gallet, Watts, and Frazer, 1963]. However, new shapes and new observational properties from individual spectra are still obtained during routine recordings on magnetic tapes.

4. New Directions of Research—More Specific Approach

a. Program

During the same period some new types of studies have been undertaken at a few laboratories. They can be characterized as systematic attempts to relate the individual VLF emission events to other geophysical phenomena, and to verify in detail some predicted properties. These studies can be classified in the following way:

1. Magnetically conjugate point studies.
2. Relationship between VLF emissions and precipitation of high energy electrons upon the low ionosphere.
3. Observation of echoes from sufficiently strong discrete VLF emissions, and establishment that the *deformation* from one signal to the next is due to the dispersion of electromagnetic waves propagated and reflected exactly like whistlers.
4. Study of the repetitive VLF emissions, which present periodically the same spectral shape. These are called "VLF Pulsations" for convenience.
5. *Continuous* observations at a network of stations, in addition to the ordinary magnetic tape recordings of high time resolution, which are necessarily limited to a sampling of two minutes every hour. These continuous observations of the VLF spectrum are made by means of a new instrument called a "Hiss Recorder" which deliberately gives a low time resolution in order that one day of data occupies a length of 72 cm on 16 mm film [Watts, Koch, and Gallet, 1963]. Data reduced to such a size can be quickly searched for VLF emission events. The device scans the 0 to 10 kc/s range by sweeps of 4 sec and displays directly in real time the spectrum of the emissions. Fine structure shorter in time than 1 min is generally lost, and therefore this equipment is convenient for recording the evolution of quasi-steadystate VLF phenomena; such as the VLF hiss. Although it is rarely possible to distinguish an isolated VLF event shorter than 1 min on the hiss recorder, the fine structure of VLF events of longer duration can easily be distinguished.

Several new types of long duration VLF events have already been found with this instrument.

b. Some New Results

1. Probably the most important of these studies are those under (1): Magnetically conjugate point studies. In particular, all the other observations in (2), (3), (4), and (5) are also included in this program. Both Stanford University and the National Bureau of Standards maintain several pairs of stations, mainly between Antartica and Northern Canada. The Bureau has a pair from Southern New Zealand to Alaska corresponding to $L=2.5$ (L is the McIlwain geomagnetic coordinate characterizing the line of force) [Gallet and Koch, 1963], and two other pairs corresponding to $L=4.0$ and $L=6.8$. These two last pairs are part of a more comprehensive program, in which several other types of geophysical observations are made in parallel with the VLF emissions: study of the high energy electron precipitation by means of riometers, airglow, and geomagnetic micropulsations.

In 1960 Helliwell indicated [Helliwell and Morgan, 1960] that "No cases of the same VLF emission forms occurring at conjugate stations have been found, indicating that the generation mechanism is highly asymmetrical with respect to the geomagnetic equator."

The present series of conjugate point observations in a large number of cases suggest an opposite conclusion. In particular, from long duration events observed with the hiss recorder and collected over a period of a year and a half, spectra have been found to be remarkably alike in both hemispheres, starting and ending simultaneously. In some cases. these events are also present at other northern stations, but in most cases the events are present only at the conjugate points.

2. Using records from the Whistlers-West network of IGY stations, it has been possible to observe a few good cases of the same VLF emission at the approximately conjugate point stations Anchorage (Alaska) and Dunedin (New Zealand). A record illustrating the first excellent case of VLF pulsation was observed the 8 August 1958, 15:35 U.T. The record is much weaker at Dunedin, already far away from the correct conjugate point. The same observation in the southern hemisphere was obtained at Macquarie Island in exact time coincidence with the Dunedin observations. The pulsations were in exact *opposition of phase* at Anchorage and Dunedin. A total of 105 re-emissions keeping exactly the same shape and about the same amplitude was observed at each station during the 2 min of magnetic tape records. The complete period was 1.06 sec. From the period and using approximate knowledge of the line of force, the electron energy was estimated to be a few to 40 kev.

3. Records have also been obtained illustrating progressive deformation of the shapes of the echoes of the initial VLF emission, due to whistler dispersion in the propagation of the electromagnetic waves. Many good observations of this type have been obtained (program 3). From the analysis of the whistler dispersion curve, using the measured delay time as a function of frequency, it has been possible in certain cases to obtain a *nose whistler* and therefore to know directly on which line of force the VLF emission was produced.

4. The program 2, on the relationship between VLF emissions and precipitation, is generally based on RIOMETER data, but also at certain periods on high altitude balloon recordings of bremmstrahlung x rays (Joint program of NBS with the University of Minneapolis. See following report by J. Winckler.)

5. Using the Hiss Recorder, a new type of very long period VLF pulsations, has been noted by NBS. An example is a record obtained the 21 December 1962 at Minneapolis. During the event starting at 12:07 U.T., 30 clearly observed very long period pulsations are superposed upon a band of hiss. The period is 56 sec. The second event starting at 14:45 U.T. contains 64 well defined long period pulsations, and the period obtained from the most well-defined 39 emissions is 41 sec.

It is believed that these very long period VLF pulsations form a class different from the short period ones. These very long period VLF pulsations may be similar to the pulsating auroral-zone x-ray events observed by D. S. Evans, particularly one very beautiful case of precipitation with a 100 second period [Evans, 1963; Anger, Barcus, Brown, and Evans, 1963]. They are also probably related to the sometimes well-defined geomagnetic micropulsations with periods of 5 to 30 sec or more observed by Campbell [Campbell and Matsushita, 1962]. As yet correlation with other geophysical phenomena has not been established.

References

Aarons, J., G. Gustafsson, and A. Egeland (1960), Correlation of audio frequency electromagnetic radiation with auroral zone micropulsations, Nature **185,** 148–151.

Anger, C. D., J. R. Barcus, R. R. Brown, and D. S. Evans (1963), Long period pulsations in electron precipitation associated with hydromagnetic waves in the auroral zone, J. Geophys. Res. **68,** (to be published).

Campbell, W. H., and S. Matsushita (1962), Auroral-zone geomagnetic micropulsations with periods of 5 to 30 seconds, J. Geophys. Res. **67,** 555–573.

Evans, D. S. (1963), A pulsating auroral-zone X-ray event in the 100-second period range, J. Geophys. Res. **68,** 395–400.

Gallet, R. M., and J. A. Koch (1963), Observations of VLF emissions and whistlers at magnetically conjugate points—I, (in preparation).

Gustafsson, G., A. Egeland, and J. Aarons (1960), Audio frequency electromagnetic radiation in the auroral zone, J. Geophys. Res. **65,** 2749–2758.

Heacock, R. R., and V. P. Hessler (1962), Pearl-type telluric current micropulsations at College, J. Geophys. Res. **67,** 3985–3995.

Helliwell, R. A., and D. L. Carpenter (Mar. 1962), "Whistlers-West" results from the IGY/IGC–59 synoptic program, Trans. Am. Geophys. Union **43,**(1), 1–9.

Helliwell, R. A., and D. L. Carpenter (Mar. 20, 1961), "Whistlers-West" results from the IGY/IGC–59 synoptic program, Stanford Electronics Laboratory Report.

Helliwell, R. A., and M. G. Morgan (1960), Summary of research on whistlers and related phenomena, URSI Bull. **12,** Pt. 4, 53–65 (as part of the Proc. URSI XIIIth General Assembly); also, J. Res. NBS **64D** (Radio Prop.), 642–646.

Jones, D. L., R. Gallet, J. M. Watts, and D. N. Frazer (Jan. 1963), An atlas of whistlers and VLF emissions—a survey of VLF spectra from Boulder, Colorado, Tech. Note No. 166, National Bureau of Standards, Boulder Laboratories, 99 pp.

Laaspere, T., M. G. Morgan, and W. C. Johnson (Nov. 1962), Chorus, hiss, and other ionospherics at stations of the "Whistlers-East" network, preprint made available for the present report (to be published).

Martin, L. H., R. A. Helliwell, and K. R. Marks (1960), Association between auroras and VLF hiss observed at Byrd Station, Antarctica, Nature **187,** 751–753.

Pope, J. (1963), A high-latitude investigation of the natural very-low-frequency electromagnetic radiation known as chorus, J. Geophys. Res. **68,** 83–99.

Tepley, L. R. (1961), Observations of hydromagnetic emissions, J. Geophys. Res. **66,** 1651–1658.

Watts, J. M., J. A. Koch, and R. M. Gallet (1963), The hiss recorder—an instrument for continuously recording the VLF emissions—observations and results since May 1961 (in preparation).

8. Energetic Particles in the Magnetosphere

John R. Winckler and Roger L. Arnoldy

The energetic particles with energies of approximately 5 kv or more in the Van Allen radiation regions are known to consist almost entirely of protons and electrons. As yet no results have been reported that give with certainty evidence for other types of energetic ions. We shall therefore divide our discussion into the recent results pertaining to the protons and to the electrons.

The best known component of the radiation belt is the proton component. This is because the experimental problems of measuring the proton energy, spatial, and time distribution are considerably simpler than in the case of the electrons. The best information about the proton energy and the spatial distribution of energy in the inner parts of the Van Allen region comes from nuclear emulsions exposed on sounding rockets. Proton detectors, sensitive in the very low energy range down to a few hundred kilovolts, have been flown on satellites penetrating throughout the entire radiation belts and have given information in the outer zone region about this component. Simple counter experiments may frequently be unambiguously interpreted in the inner zone when the known response of the counter is almost entirely due to protons which penetrate the counterwalls. Such experiments on low-altitude satellites yield much information about the spatial and time structure of the proton component. We shall give selected data representing the best current information about the energy spectrum of the trapped protons in different parts of the Van Allen radiation regions. Probably the most interesting problem is the possible sources of the protons. Many sources have been suggested and will be discussed below.

We shall present a simplified summary of the present knowledge of trapped protons in the following series of statements. For detailed discussion, the reader may consult several recent review articles [Hess, 1962; Lencheck and Singer, 1962].

1. The energy spectra of protons trapped on magnetic field lines with equatorial radii R_0 less than $2R_e$ may be conveniently represented by a power law spectrum for the higher energies. The data have been summarized by Hoffman [1962] in table 1. From the table it can be seen that the shape of the spectrum for energies above about 30 Mev as measured by the different experiments remains quite constant throughout the inner zone.

2. Fan, Meyer, and Simpson [1960] observed no protons of energy above 75 Mev beyond 3500 km geocentric distance during measurements on the Explorer VI satellite.

3. The cosmic ray neutron albedo has been shown to be an adequate source to provide the observed energy spectrum and intensity of these energetic protons [Hess, 1962; Lencheck and Singer, 1962; Kellogg, 1959; Vernov, Grigorov, Ivanenko, Lebedinski, Murzin, and Chudakov, 1959]. This does not exclude the possibility of somewhat stronger sources which would not require the long lifetimes (hundreds of years) necessary for the neutron albedo source.

TABLE 1. *Comparison of power law spectra for protons from data in inner belt*

Experiment	Altitude	Mag. lat.	γ	Energy range	Total omnidirectional flux in range indicated protons/cm² sec
		Emulsions			
	km			*Mev*	
Freden and White (1959)	1230 max 1200 av	25°	1.84	75–700	800±200
Armstrong and Heckman (961)	1170 max 1080 av	22°	1.80	80–600	~⅓, flux measured by Freden and White (1959)
Naugle and Kniffen (1961)	1600	27½°	1.7	40–100	900±200
		Counters, etc.			
Holly, Allen and Johnson (1961)					
Flight 4	940	26°	1.42	>17.5	
Flight 5	1100	19°	1.68	>23	Calculated from spectrum: ~2×10^3
Explorer VI Chamber and Counter	2225 av	−28.2° av	1.65	>23.6	2.4×10^3

4. Energetic protons are not trapped at large distances (i.e. in the outer zone) where the lifetimes are probably very short as the result of continuous magnetic disturbances [Wentzel, 1961; Dragt, 1961; and Welch and Whitaker, 1959]. The source of these particles, whatever its nature, must therefore be weak.

a. In the guiding center approximation [Alfven, 1953; Northrup and Teller, 1960] three adiabatic invariants describe the motion of a trapped particle. The first invariant is the constancy of the magnetic moment of the particle's spiral motion about field lines. This invariant gives the particle's motion along field lines since it determines the value of the magnetic field at which a particular particle will turn around or mirror depending on its pitch angle in the equatorial plane. At magnetic anomalies in the earth's field, trapped particles will move further down force lines and those of small equatorial pitch angle will be lost from the trapping region by atmospheric scattering. Measurements made by Vernov, Gorchakov, Logachev, Nesterov, Pisarenko, Savenko, Chudakov, and Shavrin [1962] on the low altitude 2d and 3d Soviet earth satellites passing over the South Atlantic anomaly reveal such leakage of trapped protons.

65,000 km; λ_m = −5°; 00.15 UT			
SpL-SpB	2.9	1.8×10^6	1.2×10^5
SpH-SpB	0.8	5×10^5	2.5×10^4
302	2.4	5.4	···
SpB	0	0	···
302-SpB	···	5.4	$<1.5 \times 10^{-3}$
55,000 km; λ_m = −7°; 01.50 UT			
SpL-SpB	3.9	2.5×10^6	1.7×10^3
SpH-SpB	2.5	1.6×10^6	8×10^4
302	16	26	···
SpB	0.06	0.3	···
302-SpB	···	26	7.6×10^{-3}
45,000 km; λ_m = −6°; 03.05 UT			
SpL-SpB	5.0	3.1×10^6	2.1×10^5
SpH-SpB	4.7	2.9×10^6	1.5×10^5
302	86	1.3×10^2	···
SpB	0.28	1.4	···
302-SpB	···	1.3×10^2	3.8×10^{-2}
35,000 km; λ_m = 0°; 04.05 UT			
SpL-SpB	3.9	2.5×10^6	1.7×10^5
SpH-SpB	5.7	3.6×10^6	1.8×10^5
302	550	8.8×10^2	···
SpB	2.7	13.5	···
302-SpB	···	8.8×10^2	2.5×10^{-1}
25,000 km; λ_m = +6°; 04.50 UT			
SpL-SpB	8.4	5.3×10^6	3.5×10^5
SpH-SpB	8 8	5.6×10^6	2.8×10^5
302	8.1×10^3	1.3×10^4	···
SpB	13.6	68	···
302-SpB	···	1.3×10^4	3.8
15,000 km; λ_m = +18°; 05.30 UT			
SpL-SpB	15.5	1.0×10^7	6.7×10^5
SpH-SpB	29	1.8×10^7	9.0×10^5
302	360	5.8×10^2	···
SpB	1.0	5	···
302-SpB	···	5.8×10^2	1.7×10^{-1}

b. The second adiabatic invariant (I) is the constancy of the line integral of the particle's momentum along a field line between two mirror points. The points in space that have the same value of B (magnetic field) and I form a ring in each hemisphere [Vestine and Sibley, 1960]. A particle mirroring at this B and I will remain upon the surface or shell described by the lines of force that connect these rings. In the earth's field all the particles that drift through a given line of force will remain on approximately the same shell even though they might turn at different B values on the given force line and have correspondingly different I values. It is thus desirable to label all points in space with a number that is unique for each shell. Such a number, which is a function of B and I only and is constant along lines of force, has been defined by McIlwain [1961] and is designated the L value. For a pure dipole field, a particle shell is labeled by an L value equal to the shell's equatorial range. Measurements of the energetic trapped protons in the inner zone made with Anton 302 Geiger counters aboard several satellites clearly show the spatial distribution of the trapped particles when contours of constant counting rate are given on a B versus L plot. An example of such a plot made by McIlwain [1961] for the Explorer IV 302 counterdata is given in figure 1.

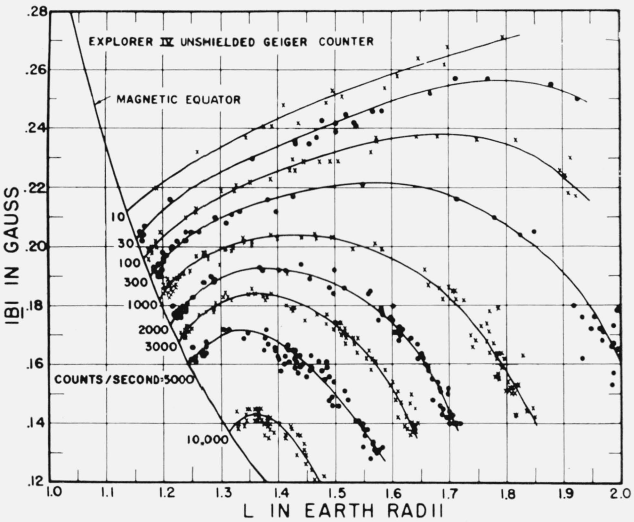

FIGURE 1. *A systemization of the intensities of particles in the inner radiation belt.*

The top rates are supposedly due to penetrating protons in the inner radiation belt above approximately 40 Mev energy. For a given value of B and L, the particles will be found located at some point in a shell determining the motion of the particles as they proceed around the earth. The lines on this figure are contours of constant counting rates. Therefore, they cut across the magnetic field and also across the lines of constant and L in the above representation. This plot is a convenient way of representing a large amount of data at points all longitudes around the earth.

The L-parameter is useful in the stable inner magnetosphere, but can be shown to be invalid during magnetic storms at large L, for example, in or above the auroral zone.

6. Measurements of the penetrating protons in the inner zone during the period October 1959 to December 1960 show counting rate increases of a factor of two or three as seen by an Anton 302 counter aboard Explorer VII [Pizzella, McIlwain, and Van Allen, 1962]. These increases are such as to preserve the geometric form of the inner zone and are of an impulsive nature occurring within a period of one to two weeks correlated with solar proton events (and/or with geomagnetic storms). These rate increases do not unambiguously mean that the intensity of the trapped radiation has increased but rather could be the result of a small shift in the spectrum such that more particles fall into the energy range above the cutoff of the detector. Figure 2 [Hoffman, Arnoldy, and Winckler, 1962] shows how a decrease in the exponent (γ) of a power law spectrum from 2 to 1.5, for example, could increase the count rate of a 302 counter by an order of magnitude for a constant intensity of trapped particles. The count rate changes observed by Explorer VII could be produced by mechanisms associated with disturbed conditions that alter the spectral character of the trapped radiation.

7. Low-energy trapped protons are observed throughout the radiation regions. Extensive observations were made by Davis and Williamson [1962]

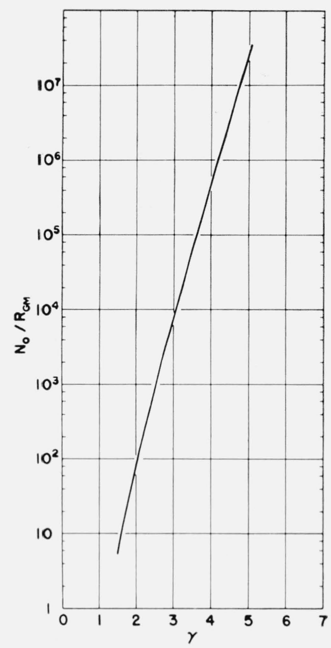

FIGURE 2. *The relative response of a geiger counter with an energy threshold to the constant multiplier* N_0 *of the integral energy spectrum expressed as a function of the exponent,* γ, *of the spectrum.*

Note the steep dependence of the rate of the counter on the exponent of the spectrum for fixed N_0.

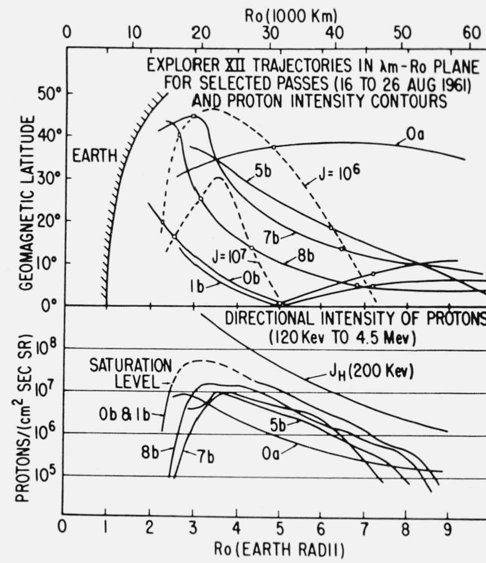

FIGURE 3. *Measurement by Davis of the low energy trapped protons on a number of different orbits of the Explorer XII satellite.*

Note that in some cases the energy density approaches that of the magnetic field at intermediate values of distance from the earth.

on the Explorer XII satellite in the energy range between 120 kev and 4.5 Mev (fig.3). The proton intensity peaks on a dipole field line having an R_0 value of about 3.5 R_e where the maximum intensity is 6×10^7 protons ($cm^{-2} \cdot sec^{-1} \cdot ster^{-1}$). The proton spectra may be approximated by $\exp(-E/E_0)$ with for example, E_0 values of 400, 120, and 64 kev at value, of R_0 equal to 2.8, 5.0, and 6.1 R_e respectively.

8. Rocket measurements of Bame, Conner, Hill, and Holly [1962] have shown that protons having energies down to 1 Mev are trapped on field lines with R_0 between 2.5 and 3 R_e. These data agree in both intensity and spectral slope for proton energies around 1 Mev with the measurements of Davis made on similar field lines.

9. Nuclear emulsions exposed on sounding rockets have measured the proton spectrum down to about 10 Mev energy [Heckman and Armstrong, 1962; Naugle and Kniffen, 1961]. A study of the proton spectra as a function of position in the inner zone showed that at higher latitudes the slope of the spectrum below 30 Mev steepens considerably (fig. 4). At about 33° magnetic latitude the spectrum is given by $J(E) \approx 3.2 \times 10^6 \cdot E^{-4.5}$ protons ($cm^{-2} \cdot sec^{-1} \cdot ster^{-1} \cdot Mev^{-1}$). An extrapolation of the Naugle and Kniffen spectrum down to 1 Mev energy shows that it has a shape essentially the same as the spectrum measured by Bame, Conner, Hill, and Holly [1962] at a similar latitude but larger altitude (fig.5).

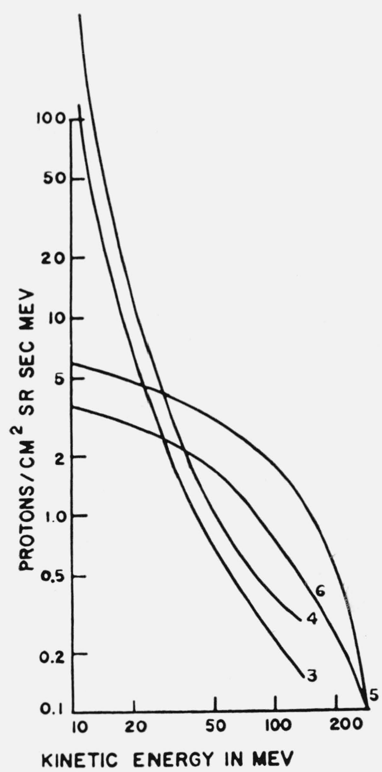

FIGURE 4. *Proton energy spectra measured by Naugle and Kniffen for different positions along the vehicle trajectory as follows:* .3L=1.79, .4L=1.72, .5L=1.54, .6L=1.47.

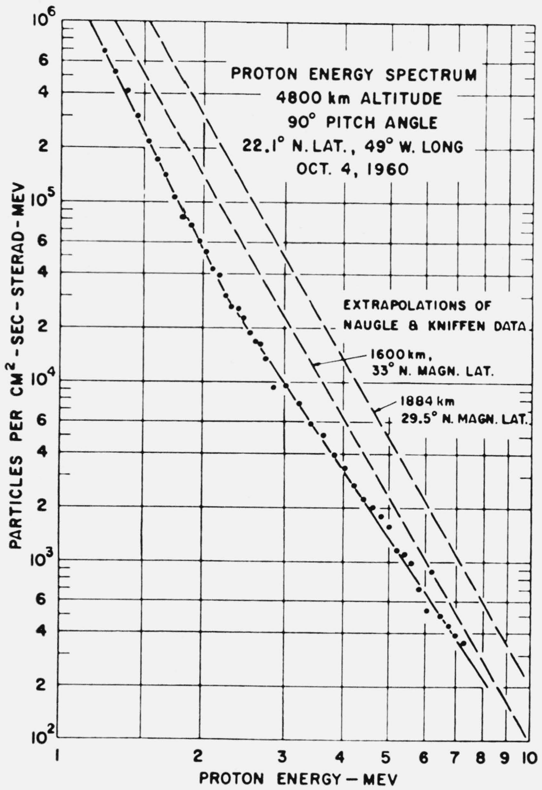

FIGURE 5. *Measurements by Bame, Connor, Hill, and Holly using an electronic proton spectrometer in the inner radiation belt.*

For comparison, the extrapolations of the emulsion data of Naugle and Kniffen into this low energy range are shown. Note that the spectra have very similar slopes in this region.

10. Several sources can be postulated for the very low energy protons: (a) decay of albedo neutrons produced by the galactic cosmic radiation, (b) decay of albedo neutrons produced by solar protons [Heckman and Armstrong, 1962; Lencheck and Singer, 1962], (c) degradation of high energy protons as a result of collisions with thermal protons [Hess, 1962], (d) a local acceleration process or processes, (e) direct solar injection. Sources (a), (b), and (c) prove to be untenable [Hess, 1962] when an attempt is made to supply the large energy flux of 50 ergs/cm²-sec-ster, measured at 1000 km altitude [Freeman, 1962] and interpreted as protons from 0.5 kev to 1 Mev, and the proton fluxes measured by Davis and Williamson [1962]. Source (b) is, however, capable of producing the latitude dependence of the protons above 10 Mev measured by Naugle and Kniffen [Lencheck and Singer, 1962]. Hess [1962] raises an objection to source (e) since emulsion data have yet to measure a flux of trapped alpha particles consistent with the measured percentage of H_e nuclei in solar cosmic rays [Freier, 1963] at balloon altitudes. However, emulsion stocks flown thus far in rockets were shielded to the extent that alpha's of the same rigidity as 30-Mev protons or less could not be measured. It remains for future data to ascertain the absence or presence of low energy alpha particles. The argument is, however, a valid one against the direct solar injection of the high energy protons of the inner zone. It might well be that the trapped protons have several sources where the required strength of a given source depends upon the energy range under consideration.

11. The total kinetic energy of the trapped low energy protons is greater than that of any other known population of trapped particles, and thus their disturbance of the geomagnetic field is greatest. Akasofu, Cain, and Chapman [1962] calculated the disturbance for a model proton belt which closely approximated the prestorm belt measured by Davis. The result predicts a decrease in the surface equatorial field of 40γ. Measurements of trapped protons by Davis during the main phase of the September 30, 1961 geomagnetic storm give intensities greater by a factor of three than the prestorm values in the region from 3 to 4.5 earth radii. Using these data Akasofu calculated the additional disturbance which would result if the storm time increase existed at all values of pitch angles. The results predicted an 80γ additional decrease which is to be compared with the D_{ST} values of 60γ to 30γ on 1 and 2 October 1961. Thus one may hypothesize that the main phase decrease was produced by the trapped protons of energy between 120 kev and 4.5 Mev.

12. It is well established that protons corresponding to the same energy range found in the trapped radiation are produced by the sun and are subsequently found near the earth. For example, plasma probes detect magnetic storm associated protons below 10 kev energy. Balloons and rockets at high latitudes, and satellites and space probes outside the magnetosphere have measured on many occasions solar flare produced particles from several hundred kev up to several bev kinetic energy. It is also known that these particles invade the magnetosphere temporarily during solar flare events to surprisingly low latitudes [Winckler and Bhavsar, 1960]. Solar protons of energy between 1 and 15 mev have been detected on magnetic shells having $R_o > 2.5\ R_e$ [Pieper, Zmuda, Bostrom, and O'Brien, 1962]. These particles are known to produce the familiar polar cap blackouts. However, there is no evidence of permanent trapping associated with the temporary detection of these solar particles.

Electrons

Knowledge of the electrons in the Van Allen radiation regions has been complicated by difficulties in measurement and in interpretation of measurements. Improvement in measurements has come within the last two years, but this increase in knowledge has, at the same time, revealed in greater detail the great complexity of the electron spectra, spatial distribution, and time variations. There is no production or injection mechanism which has been identified with certainty as the source of the observed electrons—except the high altitude nuclear explosions which have given rise to artificial electron belts in the inner zone. However, it appears that at least one source of the energetic natural electrons above 10 kev may be ruled out, namely direct injection from solar plasma.

We shall begin our simplified summary by discussing flux and spectral measurements of the naturally occurring electrons in the inner regions.

1. Magnetic spectrometer measurements have been made by Walt, Chase, Cladis, and Imhof [1960] and Cladis, Chase, Imhof, and Knecht [1961] with a sounding rocket at 920-km altitude for lines of force with equatorial radii, R_0, between 1.95 and 2.4 R_e. The spectrum, determined in four channels between 100 and 1000 kev, constitutes one of the earliest and best spectral measurements of trapped electrons. The results may be well represented by the equation $AE^P \exp(-E/E_0)$ ($\text{cm}^{-2}\cdot\text{sec}^{-1}\cdot\text{kev}^{-1}$) with $P=1.6$ and $E_0=45$ kev. The constant A is determined so that the integral omniflux above 50 kev is $4.2\pm0.8\times10^6$ electrons ($\text{cm}^{-2}\cdot\text{sec}^{-1}$).

Holly, Allen, and Johnson [1960] determined the electron flux between 50 and 450 kev in several energy intervals, and at altitudes between 900 and 1500 km close to the geomagnetic equator. The spectral shape is similar to the Walt spectrum, and at 1100 km the flux is approximately 10^5 ($\text{cm}^{-2}\cdot\text{sec}^{-1}$) above 50 kev. This flux value is considerably lower than the other four measurements discussed here.

From the Injun satellite, an energy spectrum below 100 kev has been obtained using small magnetic electron spectrometers [Pizzella, Laughlin, and O'Brien, 1962], given by $N(E)\simeq10^5 \exp(-E/160)$ electrons ($\text{cm}^{-2}\cdot\text{sec}^{-1}\cdot\text{kev}^{-1}$). The integrated flux above 50 kev is approximately 10^7 ($\text{cm}^{-2}\cdot\text{sec}^{-1}$). These values are applicable at 1000 km ($R_0\approx1.2$ R_e) altitude near the equator.

Frank and Van Allen [1962], also using Injun satellite data from an Anton-type 213 thin-window Geiger counter in a similar region, found an integrated omnidirectional electron flux above 40 kev of 1×10^7 ($\text{cm}^{-2}\cdot\text{sec}^{-1}$).

Hoffman [1962], from the scintillation counter flown on Explorer VI, together with the Anton-type 302 counter and ion chamber, was able to make a flux estimate for electrons on the $R_0=1.7$ R_e line of force at $\lambda=-28°$ geomagnetic latitude and 2225 km altitude. If the response of the scintillator was primarily to electrons >500 kev, the flux was 1×10^7 ($\text{cm}^{-2}\cdot\text{sec}^{-1}$). If the response was primarily between 200 and 500 kev, then a value of 2×10^9 ($\text{cm}^{-2}\cdot\text{sec}^{-1}$) would apply.

2. The inner zone values discussed in (1) are probably characteristic of the natural radiation. Many attempts have been made to account for these electrons by the neutron decay hypothesis [e.g., Hess, 1962], but with little success, especially at low energies where the flux is too high and the spectra too steep to be characteristic of neutron decay products. One must therefore postulate a local accelerator source for the low energy electrons. This local acceleration may, at the same time, contribute throughout the spectrum. The relative importance of the weak neutron source and this local accelerator depends on the inner zone electron lifetimes. Measurements of the electron lifetimes have recently been made on the artificial belt created by the Johnston Island nuclear test of July 1963, to be discussed in the next section.

3. It is known that artificial radiation belts consisting of β-decay electrons from high altitude nuclear explosions have been produced. High fluxes of electrons more intense than the natural radiation and extending well above 1 Mev in energy have been observed in the inner radiation regions from explosions over Johnston Island and other locations. The "Starfish" explosion on 9 July 1962 at 0900:09 UT occurred 400 km above Johnston Island in the central Pacific Ocean with a yield of 1.4 megatons [Symposium, J. Geophys. Res. **68,** 1963]. The fission decay electrons with energies up to 8 Mev were trapped with surprising efficiency and were observed at least out to a line of force with $R_0=2.7R_e$. The trapped flux precessed eastward and was intense enough to produce polarized synchrotron radio emission that was observable at numerous radio astronomy observatories, particularly at low latitude and at frequencies between 17 and 147 Mc/s. This observation was perhaps the most interesting and surprising result of the test. Analysis of the radiation [Ochs, Farley, Bowles, and Bandyopadhay, 1963] has given an excellent decay curve for the electrons (see fig. 6) and a total flux and energy spectrum measurement. The spectrum agrees well with that to be expected from fission β-decay electrons. For the first time, electron synchrotron radiation has been studied in a natural cosmic environment but under well-known conditions. With the same antennas [Ochs, Farley, Bowles, and Bandyopadhay, 1963] no detectable signal could be obtained from the natural inner zone electrons. The total excess number of trapped electrons has been estimated at approximately 10^{24}. In addition to fission decay electrons, neutron decay electrons with energy up to 780 kev may be expected over a very large region of space. Bomb electrons mirroring below 140 km altitude were removed from the radiation belts in a few hours. Those mirroring above 500 km at $R_0=1.25R_e$ have measured life times of many months.

It appears that after six months the residual "Starfish" electrons are concentrated in a narrow region over the equator. The loss mechanisms are thought to be principally coulomb scattering in the atmosphere and the synchrotron measurements verify this [Ochs, Farley, Bowles, and Bandyopadhay, 1963]. The emission of synchrotron radiation is a weak damping force and corresponds to a lifetime of many tens of years.

The earlier results of the "Argus" experiments and the "Teak" and "Orange" shots have been discussed in detail elsewhere [Symposium, J. Geophys. Res. **64,** 1959].

4. The energetic electrons in the outer radiation regions are dominated by the effects of solar plasma striking the magnetosphere. The outer zone was first detected with simple counters which, on the basis of current understanding, must have been counting electrons near 1 Mev energy [O'Brien, Van Allen,

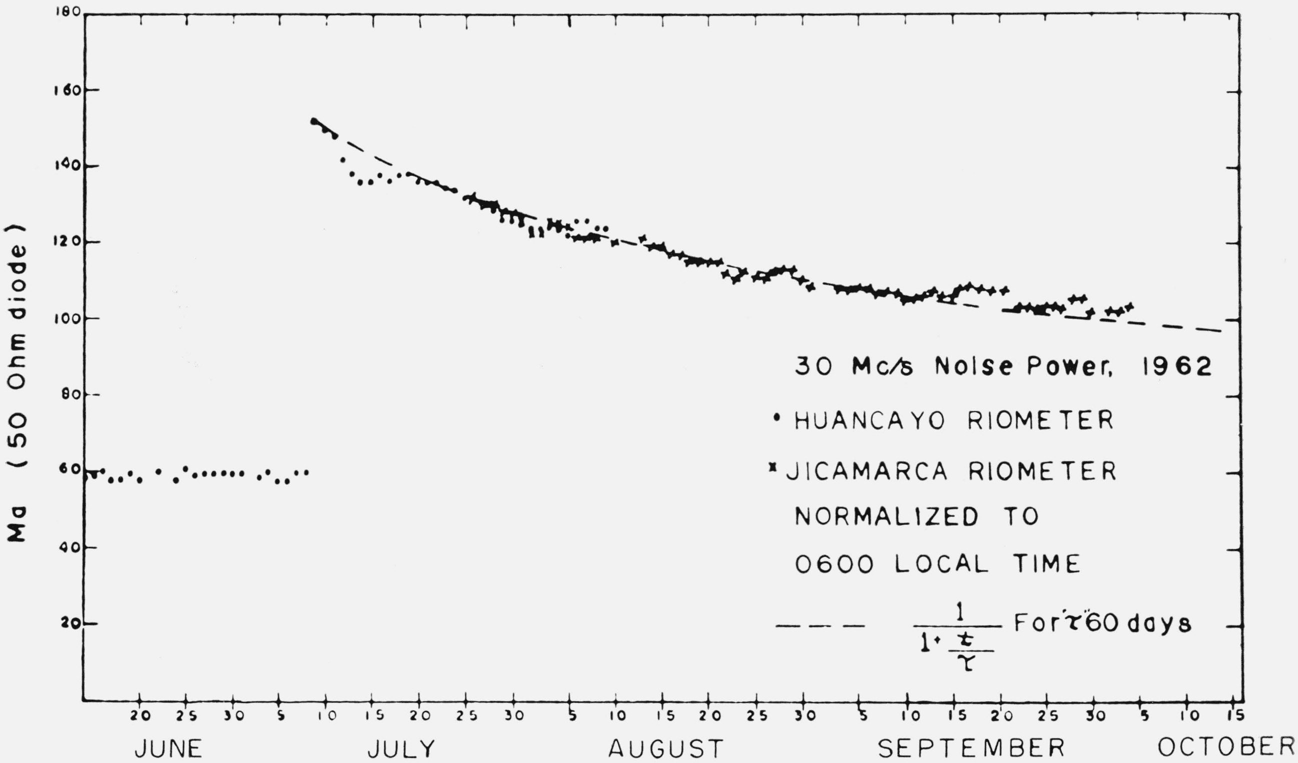

FIGURE 6. *Time history of the synchrotron radiation from electrons trapped in the geomagnetic field as a result of the "Starfish" nuclear test on July 9, 1962.* (*Ochs et al. 1963.*)

Laughlin, and Frank, 1962]. Extensive maps of the outer region in terms of these electrons were first made by the elliptically orbiting satellite, Explorer VI [Hoffman, Arnoldy, and Winckler, 1962], which also demonstrated the great effect of solar control. Some results of this study are shown in figures 7 and 8. Major changes in the equatorial pitch-angle distribution, or mirror-point densities, as well as changes in flux and spectra, follow strong geomagnetic disturbances. A characteristic pattern for the electrons near 1 Mev during a magnetic storm is an initial decrease in flux, followed by an increase and a concentration of radiation near the equator [Hoffman, Arnoldy, and Winckler, 1962; Fan, Meyer, and Simpson, 1961].

Several varieties of detectors for electrons covering the range 10 kev to 1 Mev have now been carried repeatedly through the outer zone by the very elliptical-orbit satellite, Explorer XII [Davis, 1962; Rosser, O'Brien, Van Allen, Frank, and Laughlin, 1962]. A condensed summary of the distribution for several energies from the Iowa group is given in figure 9. One notes that the electrons below 100 kev are distributed more or less uniformly over a great part of the magnetosphere, from the atmosphere out to a well-defined but variable boundary near 10 R_e. At this boundary, trapped particles of all kinds drop sharply to zero, and equally sharp changes occur in the magnetic field [Rosser, O'Brien, Van Allen, Frank, and Laughlin, 1962]. Lunik 2 measurements [Gringauz, Kurt, Moroz, and Shklonskii, 1961] show similar behavior, which is characteristic of electrons with E>200 ev. Preliminary data at large distances in the outer zone show time fluctuations of as much as 50 times in the flux of electrons near 50 kev as a result of geomagnetic disturbances [Rosser, O'Brien, Van Allen, Frank, and Laughlin, 1962]. The low energy electrons have been found to *increase* during magnetic storms at a time when the high energy component near 1 Mev was decreasing, as discussed earlier. A consistent interpretation of these facts can be found if one assumes an acceleration process which, during the initial main phase is very violent, and both adds energy and precipitates electrons of all energies. As the storm continues, the energy spectrum of the trapped electrons becomes more flat as more and more electrons are produced above 1 Mev energy, thus accounting for the post storm "build-up" observed on many occasions [Hoffman, Arnoldy, and Winckler, 1962].

5. The contours of the electron fluxes of energies 10–100 kev have not yet been mapped in detail throughout the great outer zone. However, many measurements have been made at altitudes of 1000 km or below with high-inclination or polar-orbiting satellites with a variety of detectors. Those measurements that have been analyzed and reported in the literature in enough detail to be useful are summarized as follows:

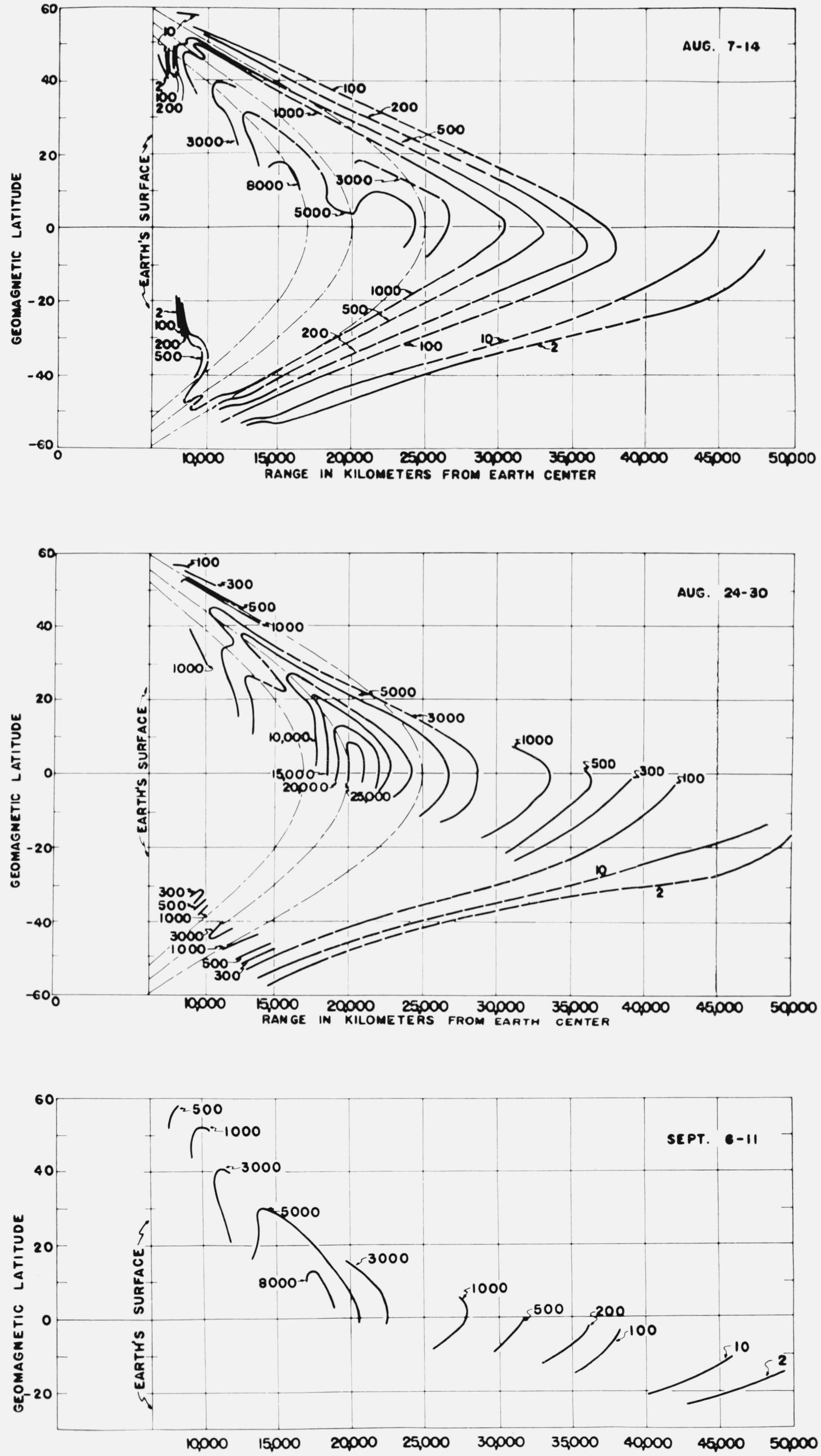

FIGURE 7. *Contours of constant counting rate for energetic electrons in the outer radiation belt obtained with the earth satellite Explorer VI.*

Top: during a quiet period before a magnetic storm. Center: increased intensities following a large magnetic disturbance. Bottom: contours obtained later following another moderate magnetic storm.

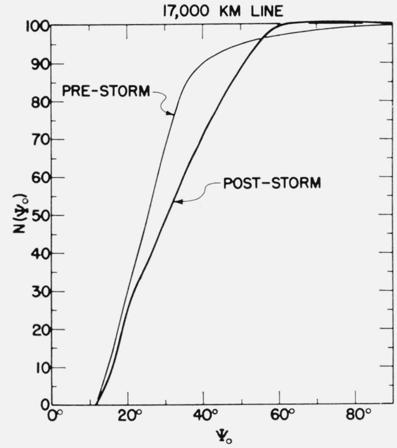

FIGURE 8. *The pitch angle distribution at the equator on a line of force at 22,400 kilometers showing the change in distribution of the energetic electrons before and after a magnetic storm.*

These angular distributions are normalized at 100. Actually the poststorm intensities are much higher in absolute value than the prestorm intensities.

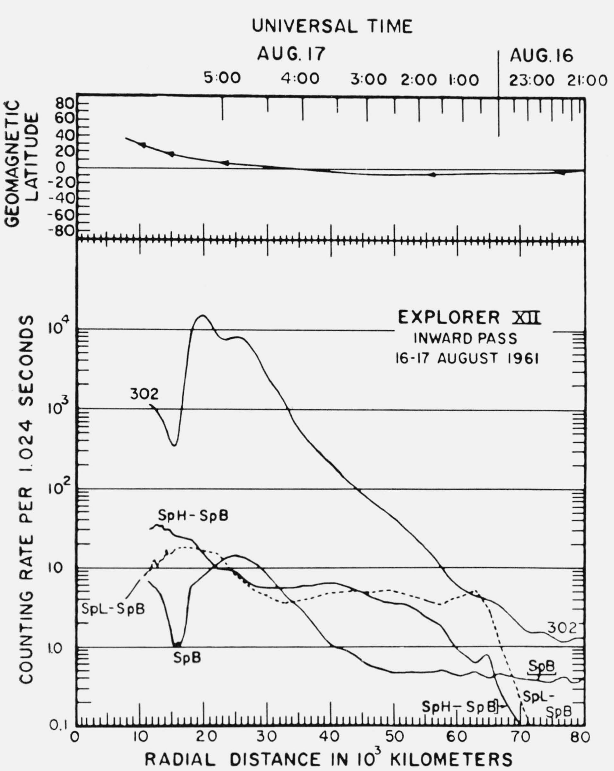

FIGURE 9. *Electrons of various energies as measured near the equatorial plane over a large range of distances by Explorer XII.*

The 302 counter is probably responding to electrons near I Mev energy and to bremsstrahlung from other electrons. SpH covers the range 80 to 100 kev and SpL 45 to 60 kev. SpB is a background counter heavily shielded with lead.

(a) An extensive analysis of outer zone electron measurements from the second and third Soviet earth satellites and from space rockets has been given by Vernov, Gorchakov, Logachev, Nesterov, Pisarenko, Savenko, Chudakov, and Shavrin [1962]. Using a scintillation counter, the outer zone electrons were detected at altitudes near 320 km and were shown to be localized at conjugate points on the magnetic field lines. At this altitude the electrons were observed at geomagnetic latitudes greater than 40°. The locus of highest intensity at 320 km coincided with predicted mirror-point paths in the two hemispheres. A typical mirror-point path for comparison purposes was chosen to be at 1500 km altitude, at 120° W longitude, and, accordingly, dips down to a low value (near the atmosphere) in the South Atlantic anomaly region. [Vernov et al., 1962] report that, in a region located between +50° and +65° north geographic latitude and between −25° and +30° east longitude, and at a $\overline{B}$ value of 0.49 oersteds and altitude 320 km, an appreciable electron flux was observed. At the conjugate point in the southern hemisphere, this $\overline{B}$ value and mirror point lies below the earth's surface. Vernov points out that these electrons are not trapped and may be locally accelerated. His results do not establish that energy has been added to magnetospheric electrons, however, since the same result could be produced by a scattering mechanism. By extending the above argument, one may conclude that most of the electrons observed by Vernov in the two high intensity belts at 320 km are, in fact, leaving the trapping region of the outer zone. If one uses the newer outer zone flux data [O'Brien, Van Allen, Laughlin, and Frank, 1962] and the arguments given by Vernov, one can estimate lifetimes between 10^4 and 10^6 seconds for electrons of several hundred kilovolts.

(b) The outer belt electrons were detected by the U.S. satellites, Explorer IV and Explorer VII, at low altitude (about 1000 km) and above 50° geomagnetic latitude in both hemispheres.

From Explorer VII data, *Forbush, Pizzella,* and *Venkatesan* (1962) and *Forbush, Venkatesan* and *McIlwain* (1961) found a consistent empirical relationship between intensity and scalar magnetic field B for different L values. This made it possible to "correct" for dependency of intensity on B, and thus to examine true time variations at any fixed L. The changes in intensity tended to be correlated negatively with the geomagnetic equatorial ring current field for $L>3.4$, and positively for $L<3.4$. Forbush et al., point out that most particles observed over Australia and North America for $2.5 \leq L \leq 3.5$ were at $\overline{B}$ values equal to or greater than those at sea level over the region of South Africa for the same L values. Consequently, these particles must be lost from the trapping region. The observed intensities of these particles over Australia measure the outflow from the outer radiation belt in a time interval less than the longitudinal drift period. This result implies a very high rate of replenishment of energetic electrons in the outer belt. These conclusions are essentially the same as those of Vernov discussed in 5(a) above. In one case, narrow zones of high intensity electrons were detected by Explorer VII at 1000 km altitude, and were closely associated with a red auroral arc covering a large range of longitudes.

6. Several additional kinds of evidence have been presented recently concerning the energy balance in the outer radiation region. These data come from directional observations of electrons in the loss cone by the Injun satellite flying at 1000 km at high latitudes, and from bremsstrahlung measurements of x rays at balloon altitudes resulting from the precipitation of electrons from the outer zone region.

A systematic study of bremsstrahlung has been made during several magnetic storms using scintillation counters on balloons flown simultaneously from 52.8° to 64.5° geomagnetic latitude ($L=2.4$ to $L=6$) [Winckler, Bhavsar, and Anderson, 1962]. The total energy loss per cm^2 of area at the atmosphere from the magnetic field by >60 kev electrons during a 12-hour storm period was found to be one or two orders of magnitude more than the "static" trapped energy in similar energy electrons measured by Explorer XII. One very intense event was observed at 69° geomagnetic latitude, restricted in longitude and latitude, which within approximately two minutes, precipitated more energy by a factor of 200 than was "statically" trapped.

The balloon observations gave new information about the time scale of the precipitation. An example is shown in figure 10. Note the many large increases with 0.1 sec widths observed during high intensity periods. These fast x-ray bursts may be ultimately connected with auroral pulsations observed visually during strong magnetic storms. The time constant is shorter than the electron bounce time between conjugate points which means that the precipitation or acceleration process must render the second adiabatic invariant (the line invariant) inapplicable. A further search was made for periodic

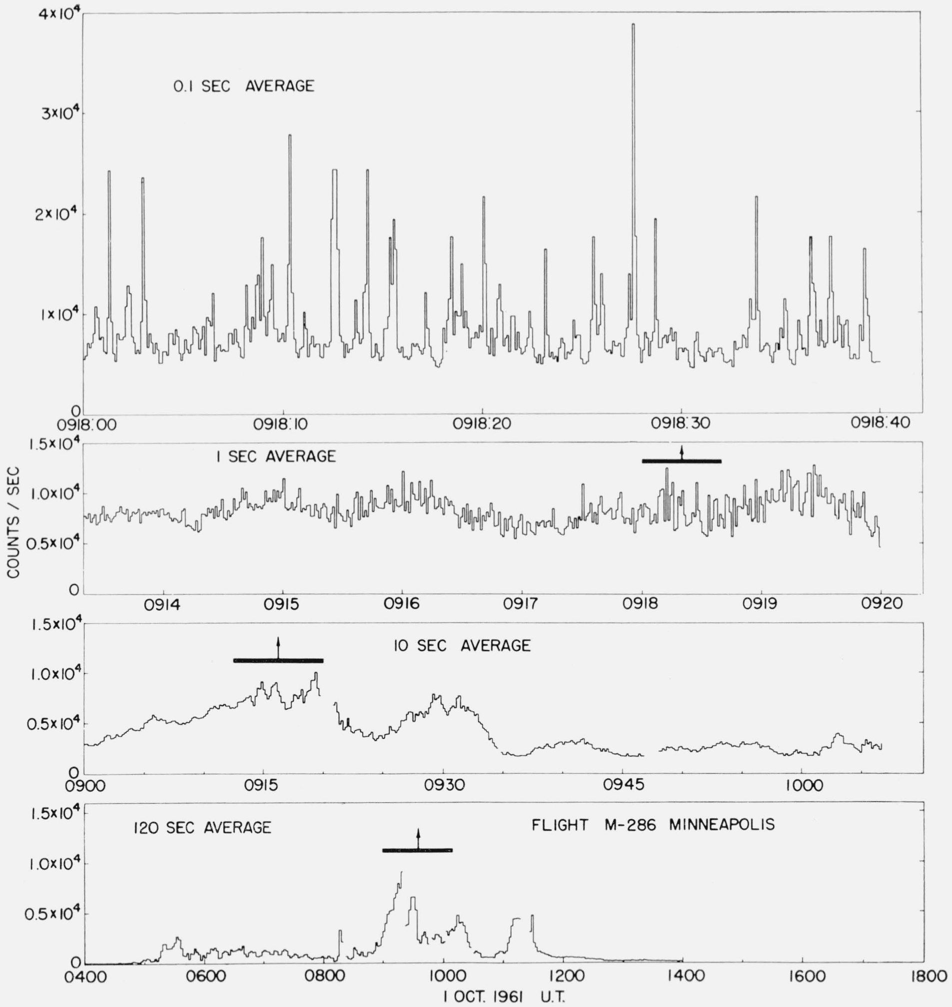

FIGURE 10. *The time structure of intense precipitation of electrons during a magnetic disturbance observed with scintillation counters flown on high altitude balloons.*

In each section of this figure, the part covered by the black line is expanded into the next section above. Note the large variability in the very long and very short periods, and the visible structure with bursts of only 0.1-second duration.

variations and both a power spectrum and Chree analysis show the presence of recurrent x-ray variations occurring at the bounce period for electrons of the energy studied, and at multiples of the fundamental bounce period.

7. In summary, all of the outer zone electron measurements discussed above indicate a continuous energy input into the outer zone which reveals itself as the outflow of electrons. This source during magnetically disturbed periods can become very strong. No other known mechanism but the solar plasma streams seems capable of supplying this energy. Measurements with detectors aboard the deep space probes Pioneer V [Arnoldy, Hoffman, and Winckler, 1960] and Mariner II [Science, 1962], however, rule out the possibility of direct solar injection into the magnetosphere of particles having energy typical of those measured in the trapping region. One must note that electron measurements made in the outer zone at large distances cannot distinguish between electrons in the process of being accelerated and *in transit* through the trapping regions, and the statically trapped electrons. The measurements at large range, however, are essential to determine the boundaries of the magnetosphere, the energy spectra, and changes in energy spectra of observed electrons, and measurement of particles responsible for the magnetic storm current systems.

The scope of this paper has not included a discussion of the many important and interesting cosmological and geomagnetic problems of the galactic cosmic rays. However, their significance in populating the inner radiation zone was discussed in the first section, and the reader may consult many excellent summaries of cosmic ray physics. (See for example the Kyoto Conference Proceedings, 1962, Vol. 11 and Vol. 111.)

References

Akasofu, Syun-I, J. C. Cain, and S. Chapman (1962), The magnetic field of the quiet-time proton belt, J. Geophys. Res. **67,** 2645.

Alfven, H. (1950), Cosmical Electrodynamics, 237 pp. (Oxford University Press, London).

Armstrong, A. H., and H. H. Heckman (1961), Flux and spectrum of charged particles in the lower Van Allen belt, Bull. Amer. Phys. Soc. **6,** 361.

Arnoldy, R. L., R. A. Hoffman, and J. R. Winckler (1960), Solar cosmic rays and soft radiation observed at 5,000,000 kilometers from earth, J. Geophys. Res. **65,** 3004.

Bame, S. J., J. P. Conner, H. H. Hill, and F. E. Holly (1963), Protons in the outer Van Allen belt, J. Geophys. Res. **68,** 55.

Cladis, J. B., L. F. Chase, Jr., W. L. Imhof, and D. J. Knecht (1961), Energy spectrum and angular distribution of electrons trapped in the geomagnetic field, J. Geophys. Res. **66,** 2297.

Davis, L. R., and J. M. Williamson (1962), Low energy trapped protons, Third International Space Science Symposium and COSPAR Meeting, Washington, D.C.

Dragt, A. J. (1961), Effects of hydromagnetic waves on the lifetime of Van Allen radiation protons, J. Geophys. Res. **66,** 1641.

Fan, C. Y., P. Meyer, J. Simpson (1960), Trapped and cosmic radiation measurements from Explorer VI, Space Research: Proc. of First International Space Science Symposium, 910 (North Holland Publishing Co., Amsterdam).

Fan, C. Y., P. Meyer, and J. Simpson (1961), Dynamics and structure of the outer radiation belt, J. Geophys. Res. **66,** 2607.

Forbush, S. E., D. Venkatesan, and C. E. McIlwain (1961), Intensity variations in outer Van Allen radiation belt, J. Geophys. Res. **66,** 2275.

Forbush, S. E., G. Pizzella, and D. Venkatesan (1962), The morphology and temporal variations of the Van Allen belt, October 1959 to December 1960, J. Geophys. Res. **67,** 3651.

Frank, L. A., and J. A. Van Allen (1962), Intensity of electrons in the earth's inner radiation zone, Tech. Rept. SUI 62–27, Iowa City, Iowa.

Freden, S. C., and R. S. White (1959), Protons in the earth's magnetic field, Phys. Rev. Letters **3,** 9.

Freeman, J. W. (1962), Detection of an intense flux of low-energy protons or ions trapped in the inner radiation zone, J. Geophys. Res. **67,** 921.

Freier, P. S. (April 1963), Emulsion measurements of solar α-particles and protons (to be published in J. Geophys. Res.).

Goddard Symposium on the Artificial Radiation Belt from the July 9, 1962 Nuclear Detonation, J. Geophys. Res. **68.**

Gringauz, K. I., V. G. Kurt, V. I. Moroz, and I. S. Shklovskii (1961), Ionized gas and fast electrons in the earth's neighborhood and interplanetary space, Artificial Earth Satellites **6,** 130 (Plenum Press, New York).

Heckman, H. H., and A. H. Armstrong (1962), Energy spectrum of geomagnetically trapped protons, J. Geophys. Res. **67,** 1255.

Hess, W. M. (1962), Energetic particles in the inner Van Allen belt, Space Sci. Rev. **1,** 278.

Hoffman, R. A., R. L. Arnoldy, and J. R. Winckler (1962a), Observations of the Van Allen radiation regions during August and September 1959, Pt. III, J. Geophys. Res. **67,** 1–12.

Hoffman, R. A., R. L. Arnoldy, and J. R. Winckler (1962b), Observations of the Van Allen radiation regions during August and September 1959, Pt. VI, J. Geophys. Res. **67,** 2595.

Holly, F. E., L. Allen, Jr., and R. G. Johnson (1960), Radiation measurements to 1500 kilometers altitude at equatorial latitudes, J. Geophys. Res. **66,** 1377.

Kellogg, P. J. (1959), Possible explanation of the radiation observed by Van Allen at high altitudes in satellites, Nuovo Cim. **11,** Series X, 48.

Lenchek, A. M., and S. F. Singer (1962), Geomagnetically trapped protons from cosmic ray albedo neutrons, J. Geophys. Res. **67,** 1263.

McIlwain, C. E. (1961), Coordinates for mapping the distribution of magnetically trapped particles, J. Geophys. Res. **66,** 3681.

Naugle, J. E., and D. A. Kniffen (1961), The flux and energy spectra of the protons in the inner Van Allen belt, Phys. Rev. Letters **7,** 3.

Northrop, T. C., and E. Teller (1960), Stability of the adiabatic motion of charged particles in the earth's magnetic field, Phys. Rev. **117,** 215.

O'Brien, B. J., J. A. Van Allen, C. O. Laughlin, and L. A. Frank (1962), Absolute electron intensities in the heart of the earth's outer radiation zone, J. Geophys. Res. **67,** 397.

Ochs, G. R., D. T. Farley, Jr., K. L. Bowles, and P. Bandyopadhay (1963), Observations of synchrotron radio noise at the magnetic equator following the high-altitude nuclear explosion of July 9, 1962, J. Geophys. Res. **68,** 701.

Pieper, G. F., A. J. Zmuda, C. O. Bostrom, and B. J. O'Brien (1962), Solar protons and magnetic storms in July 1961, J. Geophys. Res. **67,** 4959.

Pizzella, G., C. E. McIlwain, and J. A. Van Allen (1962), Time variations of intensity in the earth's inner radiation zone, October 1959 through December 1960, J. Geophys. Res. **67,** 1235.

Pizzella, G., C. O. Laughlin, and B. J. O'Brien (1962), Note on the electron energy spectrum in the inner Van Allen belt, J. Geophys. Res. **67,** 3281.

Rosser, W. G. B., B. J. O'Brien, J. A. Van Allen, L. A. Frank, and C. O. Laughlin (1962), Electrons in the earth's outer radiation zone, J. Geophys. Res. **67,** 4533.

Symposium on scientific effects of artificially introduced radiation at high altitudes (1959), J. Geophys. Res. **64.**

The mission of Mariner II; Preliminary observations (1962), Science **138,** 1095.
Vernov, S. N., N. L. Grigorov, I. P. Ivanenko, A. I. Lebedinski, U. S. Murzin, and A. E. Chudakov (1959), Possible mechanism of production of terrestrial corpuscular radiation under the action of cosmic rays, Soviet Phys. Doklady **4,** 154.
Vernov, S. N., E. V. Gorchakov, Yu. I. Logachev, V. E. Nesterov, N. F. Pisarenko, I. A. Savenko, A. E. Chudakov, and P. I. Shavrin (1962), Investigations of radiation during flights of satellites, space vehicles, and rockets, J. Phys. Japan: Proc. International Conference on Cosmic Rays and the Earth Storm **17,** Suppl. A–11, 167.
Vestine, E. H., and W. L. Sibley (1960), The geomagnetic field in space, ring currents, and auroral isochasms, J. Geophys. Res. **65,** 1967.
Walt, M., L. F. Chase, Jr., J. B. Cladis, and W. L. Imhof (1960), Energy spectrum and altitude dependence of electrons trapped in the earth magnetic field, Space Research: Proc. First International Space Science Symposium, 910 (North Holland Publishing Co., Amsterdam).
Welch, J. A., and W. A. Whitaker (1959), Theory of geomagnetically trapped electrons from an artificial source, J. Geophys. Res. **64,** 909.
Wentzel, D. G. (1961), Hydromagnetic waves and the trapped radiation, J. Geophys. Res. **66,** 359.
Winckler, J. R., and P. D. Bhavsar (1960), Low energy solar cosmic rays and the geomagnetic storm of May 12, 1959, J. Geophys. Res. **65,** 2637.
Winckler, J. R., P. D. Bhavsar, and K. A. Anderson (1962), A study of the precipitation of energetic electrons from the geomagnetic field during magnetic storms, J. Geophys. Res. **67,** 9.

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