We believe that the present experiment is significant in that we have shown that a mirror machine is capable of containing a plasma for seconds at densities of 10^7 cm^{-3} with charge exchange as the only apparent mechanism for particle loss. Our future work will be undertaken to increase the density of stored ions, to study the extent of orbital disorganization, and to investigate the homogeneity of the ion distribution.

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*Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

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EVIDENCE ON THE LAMINAR NATURE OF THE EXOSPHERE OBTAINED BY MEANS OF GUIDED HIGH-FREQUENCY WAVE PROPAGATION

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The purpose of this Letter is to report the results of a series of experiments which take advantage of the laminar structure of the exosphere for testing the existence and properties of the sheets at large distances above the earth. In addition, it is suggested that this new mode of propagation may be useful for observing, in a quasi-continuous manner from ground observations, the characteristics of the permanent ring current, recently observed in Explorer VI and Pioneer V measurements.[1]

It has been known for some years[2] that the structure of the earth's exosphere seems to be somewhat fibrous, in the sense that the electron density distribution has slight increases distributed in thin sheets or columns along the magnetic field lines. This property is evidenced mainly by the observations made on "whistlers."[3] These are a very specific type of natural radio signals of very low frequencies propagating along the curved magnetic lines of force and generated by lightning discharges. The observations show that quite often the signals are guided along several, well-separated, discrete paths. Also, the existence of long trains of echoes, in which the signal is reflected back and forth many times between the two ends of the line of force with a remarkably small total attenuation, requires that the waves be guided very efficiently within such columns or sheets, in a way similar to the guided propagation of light in long glass fibers ("light pipes") or radio waves in dielectric waveguides. In the whistler mode the frequency of the signal has to be smaller than the electron gyrofrequency, $\omega_H = eH/mc$, and smaller than the angular plasma frequency, ω_p, given by $\omega_p{}^2 = 4\pi N_e e^2/m$. Under such conditions, the refractive index is usually very large (from 7 to 30 within the exosphere) and there are strong refraction effects, complicated by a great anisotropy and a large dispersion.

The energetic particles comprising the outer Van Allen belt have also been observed by Pioneer IV[4] and by Explorer VII,[5] the latter under disturbed conditions, to be distributed in thin layers which are remarkably sharp. The relationship between the density distribution of the high-energy electrons of the Van Allen radiation, which have a low space density, and the more numerous thermal electrons forming the bulk of the exosphere is, however, not yet determined.

The present series of experiments was stimulated by the suggestion made by Obayashi[6] of the possibility of high-frequency wave guidance through the exosphere. In this case, the frequency is well above the plasma frequency and gyrofrequency, and the refractive index is almost equal to unity; consequently, the wave velocity is very nearly that for free space. We believe, however, that guidance along the line of force is afforded by a relatively small gradient of electron density transverse to the field under circumstances where the gradient is sufficient to produce the slight bending equal to the curvature of the line of force. Also it is necessary that the wave enter the exosphere in a direction tangential to the magnetic field.

It is interesting to note, historically, that Pedersen in a 1929 paper[7] suggested the possibility of propagation along a band of electrons or ions which connects the northern and southern polar areas and he considered such bands to be formed by the magnetic field of the earth. This mode of propagation was suggested by Pedersen to provide an explanation of the long-delay echoes observed at Oslo, Norway, in 1927 by Hals[8] and later by Van der Pol and Størmer at a frequency of 9.56 Mc/sec.[9] A later search for such echoes, on frequencies of 13.455 Mc/sec (30 kw) and 20.675 Mc/sec (9 kw), was made in the period 1947-1949 by Budden and Yates,[10] and during this period echoes considered to be of long delay were not observed. Observations, however, were made at several selected intervals of an hour or two in length one day each fortnight only and, if conditions permitting such echoes exist for short periods, a small percentage of time, the relatively infrequent periods of observation may explain why long-range echoes were not detected.

The experimental work of Obayashi was performed in Japan at a geomagnetic latitude of 26°. The magnetic line originating there is about 7000 km in length and, at most, reaches a height above the magnetic equator of 1500 km. Thus, most of the propagation path lay below the exosphere in the normal ionosphere. In order to test better the properties of the exosphere, experiments conducted at a much higher geomagnetic latitude are necessary so that the radio wave may traverse sufficiently far into the exosphere. Fortunately, a transmitter located near Washington, D. C. (geomagnetic latitude 50.2°) was available for use in the present series of observations. The line of force beginning at this point, computed using spherical harmonic analysis of the geomagnetic field with 48 terms included (see Vestine and Sibley[11]), has a maximum height above the earth's surface of 10 460 km (2.64 earth radii measured from the center of the earth) and a length of 33 650 km to the corresponding magnetically conjugate point in the South Pacific.

Attempts were made on various occasions during a two-month period from late April to June of 1960 to observe the signal propagating via the suggested mode and backscattering from the ground at the point in the other hemisphere which is the magnetic conjugate of the transmitter. A high-frequency radar having a peak-pulse power output of approximately 100 kw was used. To aid in signal identification a special pulse group of two one-millisecond pulses separated in time by 8 milliseconds was transmitted at a group repetition rate of 2.5 cps. A superheterodyne receiver, with a bandwidth of approximately 1 kc/sec, was used in conjunction with a low-noise preamplifier to receive the signal of which range-time and range-amplitude presentations were photographically recorded. The antenna used for both transmitting and receiving was an array of two vertically polarized 3-element Yagis which had been designed to operate on a frequency of 13.7 Mc/sec. This was tipped upward 71° to align it with the earth's magnetic field. Observations were made only during the nighttime, because of the limited frequency range of operation imposed by the antenna and because of the marginal sensitivity of the radar, so that the benefits of low critical frequency and low absorption of the ionosphere could be utilized. Table I summarizes the periods of observations and gives the radar range and times during which a clearly recognized signal was detected.

Backscatter echoes were found to exist for a length of time ranging from a few minutes up to a period in excess of 50 minutes. The received signals were weak, and it is estimated that the transmission loss for these signals exceeded 200 db. Two echo characteristics of interest are their sharpness and range stability. Pulse broadening much greater than that caused by the receiver circuitry has not been observed. This is in contrast to the large amount of pulse elongation found in normal ground backscatter echoes propagated via the ionosphere, where energy is returned from a large area of the earth, and suggests a selective mechanism of wave guidance such that only those waves whose normals lie very close to the direction of the magnetic field are propagated via this mode. The range of an echo usually remained constant throughout the period during which it was detectable but, as may be seen in Table I, echo ranges differed from one time of occurrence to another. Figure 1 is a good example showing the stability of echo range as well as the sharpness of echo return. This record was made between the hours of 0200 and 0300 U.T. on June 9, 1960, during which time an echo at a range of 27 600 km was found to exist for more than 45 minutes, gradually weakening in strength and finally disappearing. The total propagation path distance of this echo

Table I. Summary of one set of data.

Observation period U.T. Date	Start	Stop	Echo return U.T. Start	Stop	Approximate range (km)
April 22	0100	0513			
22	0558	1309	1000	1040	25 000
25	0440	1240			
27	0500	1244			
28	0630	1149			
30	0930	1241			
May 2	0536	1205			
3-4	2235	1226	0140	0142	20 000
			0220	0222	20 000
5	0456	1225			
6	0520	1156	0645	0648	21 500
			0700	0704	22 000
			0951	0953	22 100
9	0444	1234			
10	0445	1104			
12	0529	1202	0530	0532	21 500
			0630	0635	21 500
13	0330	0950	0405	0420	24 100
			0800	0802	25 200
16	0344	0907			
18	0325	0846			
23	0346	1005			
25	0308	1026			
26	0254	0302			
28	0312	0906	0802	0815	21 600
31	0315	1006			
June 1	0325	1003			
7	0434	0903			
8	0244	0904	0605	0608	20 600
			0637	0640	20 600
			0650	0653	20 600
			0710	0729	20 600
9	0200	1007	0204	0250	27 600
10	0116	1008			
11	0319	0945	0730	0732	24 500
15	0307	0805			
16	0138	1003			
19	0409	1105			
20	0219	0900			
21	0249	0902	0300	0400	24 000

(55 200 km) exceeded by at least 13 000 km the range of round-the-world echoes which have been found by various observations made in the high-frequency and the very-low-frequency bands to range from 41 160 to 42 000 km.[12,13]

The characteristics of the echoes described above differ from those reported by Obayashi and shown in Fig. 8 of reference 6. His echoes, at ranges of about 7000 km, show continuous fluctuations in range with time and are not sharp but instead are spread out. Their characteristics and range are very similar to those of normal ionospherically propagated backscatter echoes shown by several investigators[14,15] and the trans-equatorial echoes reported by Stanford observers.[16]

All exospheric echoes received at Washington, D. C., were found at ranges which were less than the calculated field-line length and different ranges from echo to echo were observed. Shortening of field lines may be explained in terms of the combined effect of the diamagnetism and drift currents, observed at altitudes beyond 6 earth radii (Explorer VI and Pioneer V).[1] Time variations of the intensity and position of the currents are, perhaps, sufficient to account quantitatively for the change in length of the line of force even though they probably do not cause a detectable change in the strength of the magnetic field observed at the surface of the earth. Thus, it is possible that this new method of exploring the exosphere may be able to provide information on the characteristics of the diamagnetism and drift currents from observations made on the ground. An additional quantity which is measurable by this type of experiment, if our concept of the method of wave guidance is correct, is the gradient of electron density transverse to the magnetic field and in the plane containing the magnetic line. Under the conditions of our experiment (i.e., frequency and latitude) it has

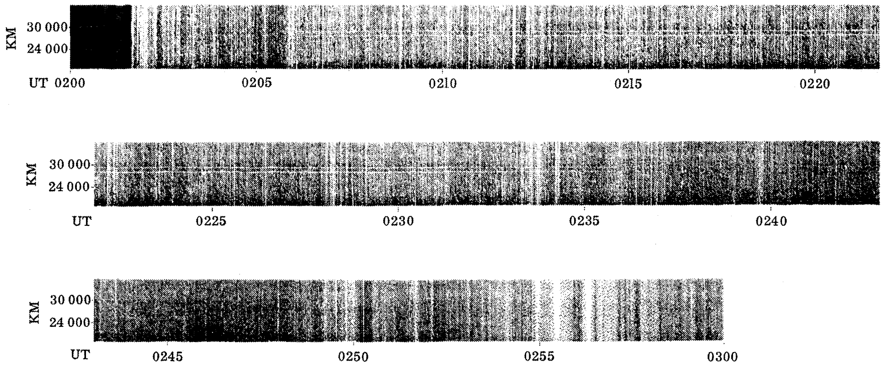

FIG. 1. Exospheric backscatter, June 9, 1960, 0200-0300 U.T.

been calculated that an electron density gradient equal to or greater than 8.1×10^{-2} electron/cc cm transverse to the field was needed for wave guidance.

Continuation of this experiment, at the same and at higher geomagnetic latitudes and transmitting nearly simultaneously on several different frequencies, is planned to permit further investigation of the variations of transverse electron density gradient and the effects of the ring current. Observations of one-way propagation, with transmitter and receiver located at magnetic conjugate points such as New Zealand and southern Alaska, are also being considered.

A more complete discussion of the conditions necessary for the high-frequency exospheric mode of propagation and the resulting information which can be deduced concerning the exosphere is planned for publication in the future.

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ELECTRICAL CONDUCTION AND BREAKDOWN IN HIGH-PRESSURE RARE GASES

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Some novel results have been obtained in the study of electrical conduction and breakdown effects in high-pressure inert gases (1-300 mm of Hg) using a high-temperature thermionic emitter as a cathode.

Two types of diodes have been used in these measurements. The first is a cylindrical-type diode which consists of a 0.010-inch diameter filament about 3.5 cm long and a cylindrical anode 1 cm in diameter and 1.25 cm long. The second type consists of a horizontal filament about 1.25 cm long and 0.010 inch in diameter with a disk anode, 1.5 cm in diameter, placed 0.5 cm above the filament. The filament was in general of tungsten, although similar results have been obtained on tantalum and rhenium. The anode material was either tungsten or tantalum sheet.

The diode assembly was mounted in a Pyrex envelope and evacuated on an ultrahigh-vacuum system. The high-vacuum pump consisted of a forepump, three-stage water-cooled oil diffusion pump and a liquid nitrogen cold trap. Included in the high-vacuum system was an Alpert-type metal valve, a molybdenum getter tube, a purified break-seal argon bottle, the tube under test, and a Bayard-Alpert ionization gauge. The system was baked out at 400°C for 8-10 hours and after degassing the pressure in the system was below 10^{-9} mm of mercury. The filaments were degassed by heating to 2500°-3000°K and the anodes were degassed at about 1000°C by electron bombardment.

After the tubes had been processed as described, anode voltage vs anode current vacuum data were taken on these diodes. The filaments were heated by a dc voltage source. The points shown as dark squares in Fig. 1 illustrate

FIG. 1. Exospheric backscatter, June 9, 1960, 0200-0300 U.T.