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# Letters

## Whistler Measurements of Electron Density and Magnetic Field Strength in the Remote Magnetosphere

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Whistler theory, supported by experiment, has shown that a whistler trace contains two types of information, one on minimum gyrofrequency along the field-line path, and the other on electron density. The minimum gyrofrequency $f_{H_{\min}}$ is determined by the relation

$$f_{H_{\min}} \simeq 2.4 f_n$$

where $f_n$ is the frequency of minimum travel time, or nose frequency, of the whistler [*Smith*, 1960] (see examples in Figure 1). Information on electron density is obtained from measurement of travel time at the whistler nose, $t_n$. This travel time is proportional to the integral of the square root of electron density along the path. As a consequence of these relations, we might expect to be able: (1) to measure the magnetospheric electron-density variations with time, and plot them as a function of geomagnetic coordinates (deduced, where appropriate, from the minimum gyrofrequency); and (2) to study geomagnetism in the remote magnetosphere, using data on observed $f_{H_{\min}}$.

Until recently the available whistler data have been limited to paths extending no farther than about 5 earth radii. Studies of the electron-density profile have been restricted to the region where $R < 5.5R_E$ [*Allcock*, 1959; *Smith*, 1960, 1961; *Pope*, 1961, 1962]. Investigations of the variations with time of magnetospheric electron density have been confined to the region where $R < 4.5R_E$. (See, for example, *Allcock and Morgan* [1958]; *Rivault and Corcuff* [1960]; *Kimpara* [1962]; *Outsu and Iwai* [1962]; *Smith* [1961]; *Carpenter* [1962*a*, *b*].) Recently, however, relatively large numbers of high-latitude whistlers have been identified. It is now apparent that whistlers regularly penetrate to regions of the magnetosphere where magnetic field strength is as low as about 60 $\gamma$. (For an undistorted dipole field, this limiting region corresponds to $R \simeq 8R_E$, where $R$ is geocentric distance in the geomagnetic equatorial plane, measured in earth radii.) The purpose of this note is to describe the new whistler data and to discuss briefly some of the possibilities for its use.

*Description of the new data.* Byrd Station in the Antarctic (70.5°S geomagnetic) is one of the principal sources of the new high-latitude data. Although the whistlers recorded at Byrd are concentrated in the period from May to late August, when the station experiences 24 hours of darkness, there is some evidence that a satisfactory (although reduced) number of high-latitude events may also be observed during the austral summer. On several magnetically quiet days in December 1961, N. Brice (private communication) recorded near the present Eights Station (75.2°S, 77.2°W geographic) a number of well-defined whistlers with associated $f_{H_{\min}}$ in the range between 50 and 4 kc/s ($R \simeq 2.5$ to $6R_E$ for a dipole field).

The occurrence pattern of high-latitude events at Byrd is roughly as follows: On a typical day from June to August, whistlers propagating on paths with minimum gyrofrequency $f_{H_{\min}} \simeq 14$ to 4 kc/s ($R \simeq 4$ to $6R_E$) are observed during three or more of the hourly 2-minute runs. On six or more days of each month during June, July, or August, one or more runs contain whistlers representing the range $f_{H_{\min}} \simeq 4$ to 1.7 kc/s ($R \simeq 6$ to $8R_E$). The lowest nose frequency observed so far is about 800 cps, corresponding to $f_{H_{\min}} \simeq 1.7$ kc/s ($H_{\min} \simeq 60$ $\gamma$; $R \simeq 8R_E$).

Spectrograms of several Byrd whistlers with values of nose frequency near 1 kc/s ($H_{\min} \simeq 80$ $\gamma$) are illustrated in Figure 1. The upper record shows a series of traces with nose

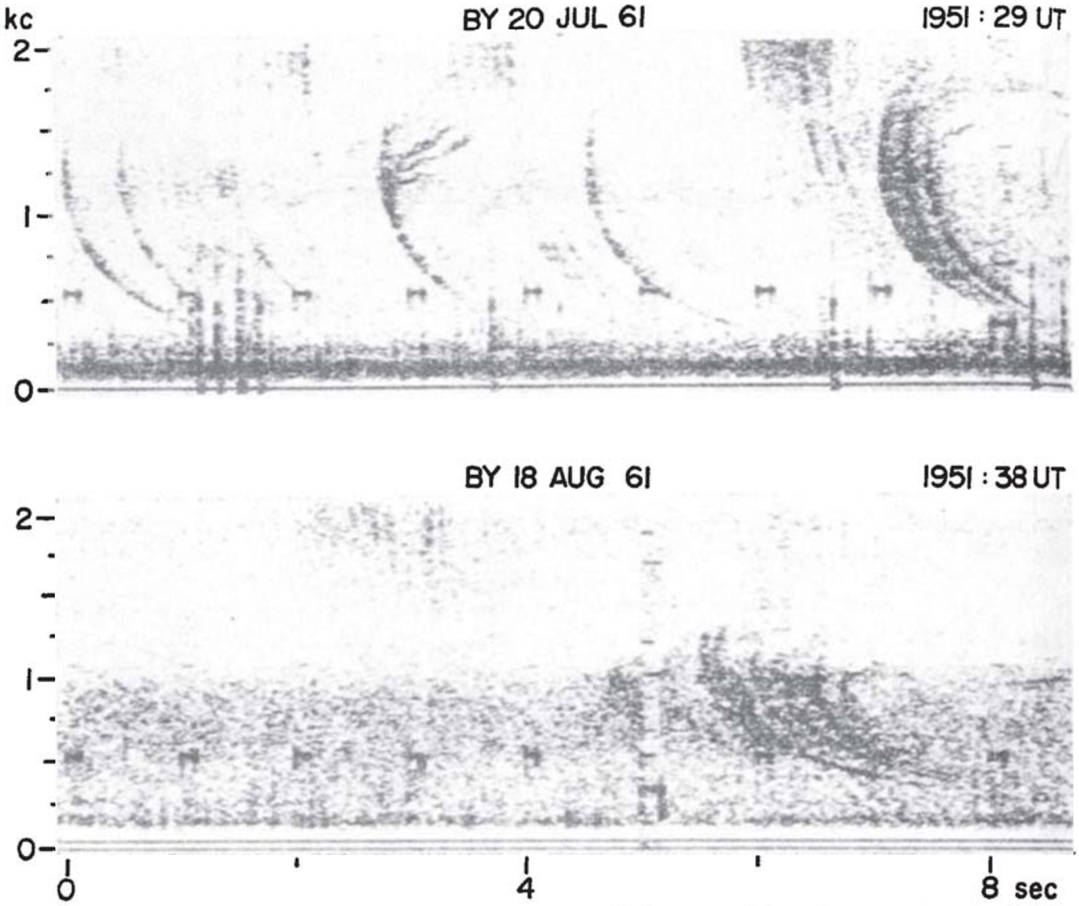

Fig. 1. Spectrographic records of high-latitude whistlers recorded at Byrd Station in the Antarctic on July 20 and August 18, 1961. The origin of the time scale is arbitrary, since the times of origin of the various whistlers have not been determined.

frequency about 1.2 kc/s and a frequency range from about 300 to 1600 cps. The detailed similarity of the various examples shows that each one originated in a separate lightning flash. Preceding several of the traces are other components with higher values of nose frequency (and thus higher values of $H_{\min}$). The lower-frequency limits of some of these components may be seen near the top of the record.

The lower record in Figure 1 shows a set of closely spaced traces with nose frequencies ranging from about 900 to 1100 cps. Because of the variation in nose frequency between successive traces, it is probable that all were produced by a single lightning flash. Note that the main group of traces is preceded (near the top of the record) by a lower-latitude group, as in the record of July 20.

There are a number of reasons why the availability of good high-latitude whistler data was not recognized previously. One reason is that many of the whistlers that have been recorded at high latitudes have been found to propagate along middle-latitude field lines [*Martin*, 1958; *Ungstrup*, 1959; *Allcock*, 1960]. A large percentage of all whistlers received at Byrd are of the middle-latitude type. Another reason is that high-latitude whistlers are relatively difficult to detect aurally or by spectrum analysis, because many of them occupy a band of frequencies less than 2 kc/s wide and have an upper cutoff frequency below 3 kc/s. Multispeed playback equipment helps to meet this difficulty by providing the type of expanded frequency scale shown in Figure 1. These 0- to 2-kc/s records were produced from the original 15-ips recordings by playback at 60 ips on an Ampex FR-1100.

Another problem in detecting high-latitude whistlers is the coincidence of ionospheric noise and whistler events. This difficulty can also be met by high-speed playback and the consequent improvement in resolution. The bottom record in Figure 1 shows a band of noise with maximum intensity in the range from about 500 to about 1100 cps (the noise on both records below 150 cps is partly of instrumental origin). On a normal-speed, 0- to 8-kc/s record, this band is compressed into a small fraction of the display, and the whistler traces are difficult to identify.

Still another explanation of the lack of previous knowledge about high-latitude whistlers is the pronounced diurnal variation in their occurrence at Byrd. High-latitude whistlers are more frequently observed when the field lines terminating near Byrd are on the sunlit side of the earth. This is a surprising result, since, on the basis of $D$-region absorption, we would not expect whistler activity along a given set of field lines to diminish during nighttime. Note in Figure 1 that both events were recorded during the run of 1950 UT, which corresponds to early afternoon (local time) in the conjugate area, and also that one of the records represents severely disturbed geomagnetic conditions (July 20), and the other represents extremely quiet conditions (August 18). There is a corresponding difference in the frequency-versus-time, or dispersion, characteristics of the whistlers. The events of July 20 show the low-dispersion characteristics that have previously been observed at lower latitudes during magnetically disturbed periods [*Carpenter*, 1962*b*, *c*].

*Research using the new data.* Whistlers propagating in the region where $R < 4R_E$ are a convenient source of information on magnetospheric electron density. By contrast, whistlers propagating in the region where $R > 4R_E$ are somewhat more difficult to analyze for the usual type of density information but can yield important information on magnetic field strength and on the persistence of stable propagation conditions at great heights.

For example, suppose that, over a time interval $T$, a given trace is repeated from whistler to whistler without a detectable change in its frequency-versus-time shape (cf. Figure 1, *top*). It can then be inferred that: (1) during the interval $T$, a field-line path with the observed value of $f_{H_{\min}}$ existed in the magnetosphere; (2) the electron density and magnetic field strength along the path did not change by more than a few per cent during $T$. The quantity $T$ can be obtained as a function of $f_{H_{\min}}$, time of day, magnetic conditions, etc., and will aid greatly in describing the physical state of the magnetosphere.

Another very useful quantity, related to $T$, is the whistler occurrence rate as a function of $f_{H_{\min}}$. In the past, the practice with occurrence data has been to obtain a single rate covering all whistlers observed at a single station. Unfortunately, this method obscures important latitude-dependent effects, such as those seen at Byrd. A diurnal plot of the Byrd occurrence rate for $R \simeq 2.5\text{–}3R_E$ would show a broad peak at about 0850 UT; a plot of the rate for $R \simeq 7\text{–}8R_E$ would show a peak at about 1950 UT. This kind of latitude-dependent picture may prove helpful in reconciling whistler propagation conditions with observations of chorus, a type of VLF ionospheric noise which tends to have a daytime peak at high latitudes.

An interesting question arises, namely, what is the smallest value of $f_n$ (and, thus, of $f_{H_{\min}}$) that can be observed? To date the lowest value is about 800 cps, corresponding to $H_{\min} \simeq 60\ \gamma$. However, only a preliminary investigation of the Byrd data has been made, involving a limited sample. The frequency of observation of a given $f_n$ appears to fall off rapidly at great heights, but so far the data have provided no evidence to indicate that a lower $f_n$ limit has been reached.

A study of the statistics of the lowest observed nose frequencies may show that whistlers can be used to detect the outer boundary of the geomagnetic field. This possibility is worth investigating, particularly in view of the evidence from Byrd that conditions for whistler propagation through the remote magnetosphere are favorable on the sunlit side of the earth.

The increased difficulty in studying electron density at great heights is due to corresponding uncertainty in the shape of the geomagnetic field. This uncertainty can be reduced in a number of ways, which include the use of data from magnetically quiet periods, the comparison of high-latitude results with corresponding data from lower heights, and direct study of geomagnetism through the statistics of occurrence of high-altitude whistlers. It is not supposed that the density analysis will be simple, but there is reason to believe that it is feasible. For example, it has already been found (cf. Figure 1) that magnetic storm effects show important similarities at both middle and high latitudes. It is also worth noting that the Byrd data contain many 'knee' whistlers, that is, whistlers showing evidence of a knee in the magnetospheric ionization-density profile [*Carpenter*, 1963]. The high-latitude observations are consistent with those already made at middle latitudes, and support the conclusion that the knee is a persistent phenomenon, which moves inward with increasing magnetic activity.

Whistler-mode propagation of man-made VLF signals has been under study for a number of years [*Helliwell and Gehrels*, 1958; *Helliwell et al.*, 1962], and the encouraging experimental results have led to consideration of the use in the Antarctic of a sweep-frequency transmitter capable of operating between roughly 1 and 30 kc/s. With the recent evidence of the possibility of artificial stimulation of ionospheric noise [*Helliwell*, 1962] and the evidence offered here that high-latitude whistler paths are effectively 'open' during a substantial part of the time, the potential usefulness of this device is greatly increased. The knowledge gained in the forthcoming studies of high-latitude whistlers should in a few years provide a detailed basis for determining how such a sounder can be used and how the results may be interpreted.

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