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Whistler Observations During a Magnetospheric Sudden Impulse

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Whistlers recorded at Siple, Antarctica (76°S, 84°W), show sudden changes in nose frequency (f_n) in response to a magnetospheric sudden impulse (si) on June 9, 1973. These changes are partly due to changes in local magnetic field strength and partly due to the motion of the duct under the influence of induced electric field. This example is used to illustrate how ground-based VLF radio techniques can be used to monitor the dynamic response of the magnetosphere to shocks and discontinuities in the solar wind.

Sudden changes in the solar wind pressure associated with shocks and hydromagnetic discontinuities are known to cause compression or decompression of the magnetosphere. The magnetic signatures of this phenomenon are clearly identifiable on magnetometer records on the ground [e.g., *Nishida and Jacobs*, 1962; *Matsushita*, 1962] as well as on satellites [e.g., *Nishida and Cahill*, 1964; *Patel and Coleman*, 1970]. These events are called sudden impulses (si) or storm sudden commencements (ssc) depending on whether or not they are followed by magnetic storms. Satellite observations of the solar wind have provided clear evidence that si's and ssc's are produced by irregularities in the solar wind interacting with the magnetosphere. However, quantitative relationships between the observed changes in the geomagnetic field and the solar wind parameters are not satisfactorily explained by present theory [*Siscoe et al.*, 1968; *Burlaga and Ogilvie*, 1969; *Ogilvie and Burlaga*, 1970].

Figure 1 illustrates schematically how the magnetopause and field-aligned whistler ducts are pushed closer to the earth by a sudden increase in the solar wind pressure. The purpose of this brief note is to report on whistler observations during such an event and to draw attention to the potentialities of ground-based VLF radio techniques for monitoring the dynamic response of the magnetosphere to shocks and discontinuities in the solar wind.

Figure 2 shows the si event of June 9, 1973. At the top of the figure are tracings of H component magnetograms from the low-latitude stations San Juan, Dallas, Guam, Kakioka, and Teshkent. We can clearly identify the si event starting at ~1625 UT and reaching a peak at ~1635 UT. The lower half of the figure shows the results of whistler observations at Siple, Antarctica (76°S, 84°W; $L \sim 4$). Whistler recordings were made for 1 min every 5 min. Whistler rates were sufficiently high to allow individual tracking of a number of discrete components for many hours. The nose frequencies (f_n) of four selected components are shown in the figure. The bottom horizontal scale is magnetic local time at Siple. We lack precise longitude information on whistler ducts, but we assume that they are within the station's normal viewing range of $\sim\pm2$ hours. (This estimate of Siple's viewing range is based on comparisons with simultaneous whistler records from Halley Bay, about 3 hours away in magnetic local time.)

The whistler f_n data show two different effects: (1) si-associated rapid variations between ~1625 and ~1645 UT and (2) long-term trends, not correlated with low-latitude magnetometer records, that can be interpreted in terms of duct drift motions under the influence of potential **E** field. An examination of auroral latitude magnetograms reveals magnetospheric substorm activity starting at ~1700 UT. The f_n variations during this substorm activity as well as during the quiet period preceding the si are consistent with quiet time and substorm electric field patterns recently reported by *Carpenter and Seely* [1975]. We will not discuss these long term **E** field effects in this report; we will limit our discussion to the si effect.

The whistler f_n is related to the minimum magnetic field strength along its propagation path by

$$f_n = 0.37 f_{Hm} = 10.4 B_m$$

if the minimum electron gyrofrequency f_{Hm} and f_n are measured in hertz and B_m is measured in gammas [*Park*, 1972]. The B_m scale is shown on the right-hand side of Figure 2. The extreme right-hand scale shows the corresponding equatorial radius at local noon based on an image dipole model with the magnetopause at 10 R_E. A change in f_n can be expressed in terms of two components:

$$\frac{df_n}{dt} = 10.4\frac{dB_m}{dt} = 10.4\left(\frac{\partial B_m}{\partial t} + \mathbf{v}\cdot\nabla B_m\right) \qquad (1)$$

The first term represents temporal variations of B_m, whereas the second term represents convection of the ducts into regions of different B_m (see *Block and Carpenter* [1974] for a more detailed discussion). The convection velocity **v** is given by

$$\mathbf{v} = (\mathbf{E} \times \mathbf{B}_m)/B_m^2$$

where **E** is the total electric field including induced as well as potential field. The two terms in (1) can be separately estimated as follows.

Consider the whistler component marked A in Figure 2. Between 1625 and 1635 UT, f_n increased by 350 Hz corresponding to $\Delta B_m = 33.7\ \gamma$. The contribution by the $\partial B/\partial t$ term can be estimated from a magnetospheric magnetic field model. For the purpose of illustration we assume a simple image dipole model of the day side magnetosphere with the solar wind flowing perpendicular to the dipole axis. In future studies, more sophisticated models should be applied to cases in which ΔB_m is observed simultaneously over wide L ranges. If multicomponent whistlers cover sufficiently large L ranges, observed spatial variations in ΔB_m should provide a check on the magnetospheric models used. Since the present case is not well suited for such detailed analysis, we will only give a simple illustration. In an image dipole model the equatorial B field is given by

$$B_{eq} = 31{,}200\left[\frac{1}{R_{eq}^{\,3}} + \frac{1}{(2R_M - R_{eq})^3}\right]\ \gamma \qquad (2)$$

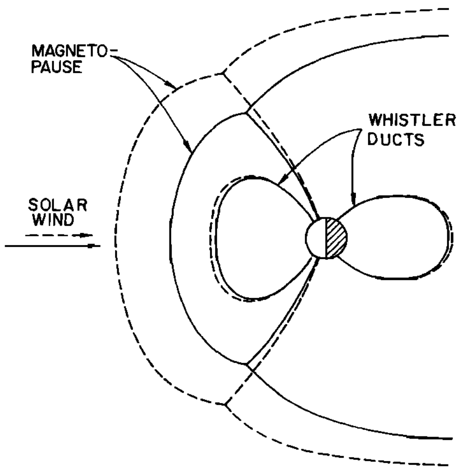

Fig. 1. A sketch illustrating compression of the magnetosphere by a sudden increase in solar wind pressure.

where R_{eq} is the equatorial distance and R_M is the equatorial position of the magnetopause, both measured in units of earth radii. Low-latitude magnetometers on the day side indicate $\Delta B_{eq} = 8\ \gamma$ at $R_{eq} = 1$ after the amplification factor of 3/2 due to induced earth currents is allowed for [*Chapman and Bartels,* 1962]. If we assume an initial value of $R_{M1} = 10$, (2) predicts a final value of $R_{M2} = 7.27$. The deviations of ΔB_{eq} from a dipole model in the initial and the final state are plotted in Figure 3. Whistler duct A initially at $R_{eq} = 4.3$ would experience an increase in B_m by 20.9 γ due to the $\partial B/\partial t$ term. The second term in (1) must contribute 12.8 γ to make the sum equal to the total increase of 33.7 γ deduced from the change in f_n. If we

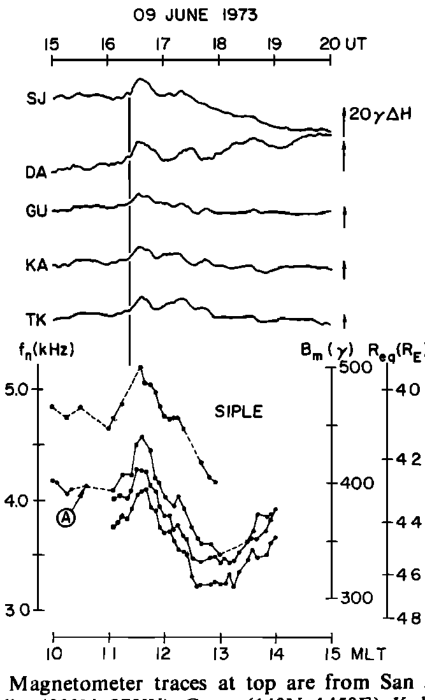

Fig. 2. Magnetometer traces at top are from San Juan (18°N, 66°W), Dallas (33°N, 97°W), Guam (14°N, 145°E), Kakioka (36°N, 140°E), and Teshkent (41°N, 69°E). The si event at 1625 UT is marked by a vertical line. Below, nose frequencies of four whistler components at Siple, Antarctica, are plotted as a function of magnetic local time. The vertical scales on the right show the minimum magnetic field strength along the whistler path and corresponding equatorial path radius in an image dipole model with the magnetopause at 10 R_E.

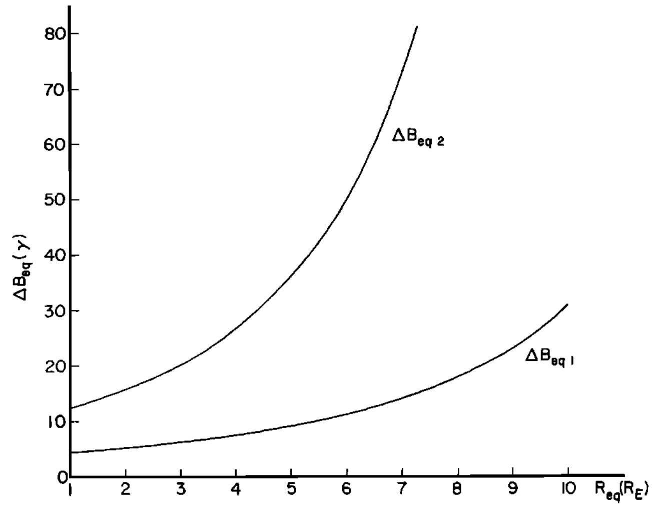

Fig. 3. Plots showing the changes in the equatorial field strength when the magnetopause moves from 10 R_E to 7.27 R_E in an image dipole model of the magnetosphere.

differentiate (2), we obtain $\nabla B_{eq} = 273.8\ \gamma/R_E$ at 4.3 R_E. This means that the duct was displaced inward by 12.8/273.8 = 0.047 R_E in 10 min during the rising portion of the si. The corresponding equatorial drift velocity and electric field are 500 m/s and 0.2 mV/m, respectively. These numbers, however, should not be taken too seriously because of the crudeness of the image dipole model. Satellite observations out to $L \sim 8$ show that the amplitude of an si does not increase beyond a factor of about 2 of the ground value [*Nishida and Cahill,* 1964; *Patel and Coleman,* 1970]. In contrast, Figure 3 predicts much larger increases than this. If we assume that the $\partial B/\partial t$ term contributed 24 γ (twice the ground value of 12 γ without counting the effects of induced currents) at 4.3 R_E, we would then estimate the equatorial drift velocity and electric field as 400 m/s and 0.15 mV/m, respectively.

The above example illustrates how ground-based whistler technique can provide useful information even at a coarse sampling rate of 1 min every 5 min. In future studies, continuous recordings can improve the time resolution to a fraction of a minute. Under favorable observing conditions, dB_m/dt can be measured in the range L = 2–6 (20 or more ducts in that L range may be excited by a single lightning stroke). With such data it may be possible to measure the propagation speed of the si disturbance and study the shielding effect of energetic magnetospheric particles discussed by *Siscoe et al.* [1968].

Whistler mode signals from VLF transmitters may be used to obtain time resolution of the order of 1 s, much better than what can be achieved through natural whistlers. *McNeil* [1970] observed changes in the phase of the NPG transmitter (near Seattle) signal received in New Zealand that were well correlated with ssc's. In this experiment, however, it was not possible to determine the whistler mode path location. If a versatile transmitter is used to send suitable frequency-modulated signals, the dispersion of these signals can be analyzed in much the same way as natural whistler signals to obtain information on the path location and electron densities along the path. Such experiments are now underway using the transmitter at Siple, Antarctica [*Helliwell and Katsufrakis,* 1974].

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