Discussion of Paper by R. L. Dowden, 'Doppler-Shifted Cyclotron Radiation from Electrons: A Theory of Very Low Frequency Emissions from the Exosphere'

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A new theory of VLF emissions from the exosphere has been postulated by *Dowden* [1962] who suggests that 'hooks' may be Doppler-shifted cyclotron radiation from bunches of electrons traveling away from the observer's hemisphere in a helix about a magnetic line of force. He further suggests that the particle bunch may mirror, giving rise to a series of hooks of similar shape separated in time by the period of oscillation of the bunch, and that observers at conjugate points would observe the series separated in time by half a period.

Assuming that Dowden's mechanism is operative and that the medium is symmetrical about the top of the magnetic field line, consider a group of particles spiraling up the line of force and generating emissions that travel back down the line of force to the observer. Suppose they emit frequency f_1 at geomagnetic latitude $\theta = \theta_1$ and time $t = -\delta$. If the propagation time for this frequency from the top of the path to the observer is τ_1, then from the point of emission it will be less by an amount, say, ρ. Thus the frequency f_1 is seen by the observer at time

$$t_- = -\delta + \tau_1 - \rho$$

The particles arrive at the top of the line of force, $\theta = 0$, at time $t = 0$, and emit the lowest frequency in the hook, f_0, which is seen by the observer at time $t = \tau_0$. They then travel on down the other side of the line of force and arrive at time $t = +\delta$ at latitude $\theta = \theta_1$, where the frequency emitted is again f_1. This wave takes a time $\tau_1 + \rho$ to propagate to the observer and arrives at time

$$t_+ = +\delta + \tau_1 + \rho$$

Thus frequency f_1 will be observed before f_0 by an amount

$$T_0 = \tau_0 - t_- = \delta + \rho + \tau_0 - \tau_1$$

and after f_0 by

$$T_0' = t_+ - \tau_0 = \delta + \rho + \tau_1 - \tau_0$$

whence

$$T_0 - T_0' = 2(\tau_0 - \tau_1)$$

If a whistler propagated over the same path as the emissions, the difference in times of arrival of frequencies f_1 and f_0 for a short (one-hop) whistler should equal $T_0 - T_0'$ *exactly*. In deriving this relationship no assumptions were made limiting frequency f_1, particle velocity,

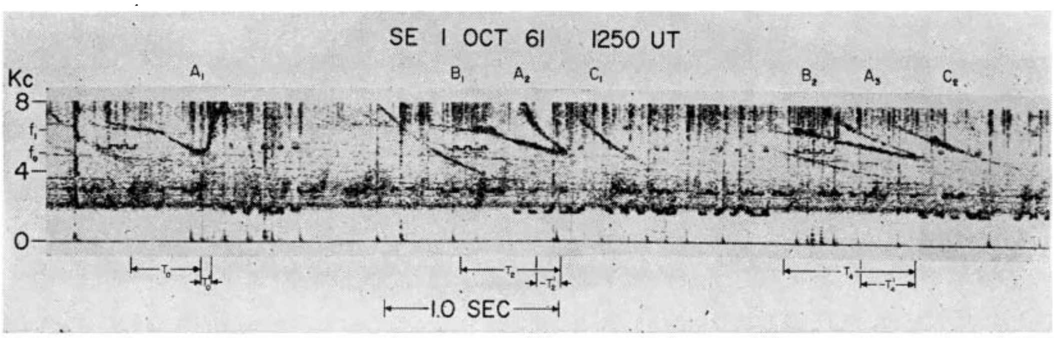

Fig. 1. Hooks (A_1, A_2, A_3) and whistlers (B_1, B_2 and C_1, C_2) echoing in the whistler mode over the same path.

TABLE 1

f_1, kc/s	f_0, kc/s	n	T_n, sec	T_n', sec	$\frac{n(T_0 - T_0')}{T_n - T_0}$	$\frac{n(T_0 - T_0')}{T_0' - T_n'}$
6.5	5.1	0	0.39	0.05		
		2	0.57	−0.14	3.8	3.6
		4	0.75	−0.31	3.8	3.8
4.5	3.8	0	0.16	0.03		
		1	0.22	−0.03	2.2	2.2
5.0	3.8	0	0.35	0.02		
		1	0.42	−0.07	4.7	3.7
4.4	3.8	0	0.17	0.02		
		1	0.22	−0.03	3.0	3.0

electron-density distribution along the line of force, or the location of the line of force.

Thus, if Dowden's theory is correct, the shape of a hook is related very simply and explicitly to the whistler-mode group delay for the line of force along which the hook is generated, and a definitive test of the theory can be made. If the hook echoes, i.e., travels in the whistler-mode back over the path to the conjugate point, frequency f_1 will be delayed by an amount $2\tau_1$ and f_0 by $2\tau_0$. For this one-hop echo, denote T_1 and T_1' the quantities corresponding to T_0 and T_0' of the hook as first observed. Then,

$$T_1 - T_0 = 2(\tau_0 - \tau_1) = T_0 - T_0' \quad (1)$$

This may be generalized for an n hop echo,

$$T_n - T_0 = n(T_0 - T_0') = T_0' - T_n' \quad (2)$$

From (2) it is seen that for echoing hooks

$$T_n + T_n' = T_0 + T_0' \quad (3)$$

for all n and any chosen frequency f_1. Further, this echo must show an increase in dispersion consistent with whistler-mode propagation.

On October 1, 1961, at 1250 UT, a series of hooks was recorded at Seattle, and at the same time, a whistler echo train (Figure 1). The frequency-delay relationship found by measuring from any hook in the series to the next is identical with that found by measuring from one whistler echo to the next. The hook was identified many times; measurements of the first three traces (Figure 1) are given in Table 1, where it is assumed that the first hook seen had not echoed. If the hook arrived first at the conjugate point and echoed to Seattle, then the applicable equation analogous to (2) is

$$T_n - T_1 = \frac{n-1}{3}(T_1 - T_1') = T_1' - T_n' \quad (4)$$

This ambiguity is removed if the hook and echo are observed at conjugate stations. On September 26, 1958, at 0135 UT, several very similar hooks were seen at Dunedin, at about 11, 32, 45, 63, 71½, 86½, and 98 seconds after the start of the recording. One-hop echoes of all these were seen at Unalaska, and several showed weak two-hop echoes at Dunedin also. Measurements were made on those at 45, 63, and 86½ seconds and their one-hop echoes; these results appear in Table 1. In this table, $n(T_0 - T_0')/(T_n - T_0)$ and $n(T_0 - T_0')/(T_0' - T_n')$ are given. As long as the hook echoes, these quantities should be equal, any inequalities indicating errors in measurement.

If the hooks were generated by the mechanism suggested by Dowden, these quantities would be equal to unity. The discrepancies clearly cannot be accounted for as errors in measurement, and it must be concluded that the hooks certainly were not generated by the postulated mechanism.

It should be noted that the path over which the emission echoed may in principle be determined by measuring the delay at two frequencies and by using the *Smith and Carpenter* [1961] technique normally applied to find nose frequencies for whistlers, from which the latitude of the end point of the path may be deduced [*Smith*, 1960].

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