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A New Interpretation of Subprotonospheric Whistler Characteristics[1]

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In the past the study of various kinds of whistlers has provided valuable information on the structure of the magnetosphere. However, one type of whistler whose study has been somewhat neglected is the so-called 'subprotonospheric' (SP) whistler. Here the propagation paths of SP whistlers are studied and a number of their characteristics explained. It is shown that horizontal gradients in the ionosphere play an important role in the reflection of ELF waves at an altitude of about 1000 km. The variations in intensity between the various components of SP whistlers observed from satellites are explained by the presence or absence of these gradients. The several components of an SP whistler, received at a point in the ionosphere, are associated with wave packets entering the lower ionosphere at different latitudes and traveling along different paths. Data from the Ogo 4 satellite are used to substantiate these explanations. A tone rising in frequency with time that is often seen with SP whistlers and proton whistlers is shown to be caused by the reflection of a downcoming SP whistler component near the ion cutoff frequency. This contradicts a previously published explanation of the rising tone as a stimulated emission. The characteristics of the rising tone are sensitive to the relative abundance of the various ions, while those of the SP whistler depend greatly on horizontal gradients in the ionosphere. The combination of the SP whistler and the riser has potential as a diagnostic probe of the plasma structure of the ionosphere.

In the past, many types of magnetospheric whistlers have been found useful in studies of magnetospheric plasma structure. Among the nonducted whistlers one that might be expected to contain substantial information about ionospheric properties is the so-called 'subprotonospheric' (SP) whistler. Figure 1 shows a sketch of an SP whistler in coordinates of frequency versus time. The whistler exhibits a series of falling tones separated in time by periods of the order of 150 ms. SP whistlers were first reported by *Carpenter et al.* [1964]. In their study they concluded that the multiple appearances of the whistler are the result of repeated propagation back and forth between an altitude of about 1000 km and the lower boundary of the ionosphere. They also found that the SP whistlers received on a satellite around 1000 km showed a systematic variation with latitude in the intensity of the various components. This variation in intensity is illustrated in Figure 2 by spectra from Ogo 4. As the satellite moves to lower latitudes, the components that follow the initial trace disappear one by one. SP whistlers are usually observed between 40° and 65° dipole latitude. Their lower cutoff frequency is higher for the later components, as can be seen from Figure 1. SP whistlers occur most often at night, within a few hours after sunset.

Smith [1964] gave a qualitative explanation for the reflection of SP whistlers around 1000 km, based on the effects of ions and the presence of horizontal gradients. *Kimura* [1966] calculated ray paths, including the effects of ions, to confirm Smith's ideas. The satellite is almost stationary in the time it takes to receive the multiple components of an SP whistler. *Kimura* [1966] therefore proposed that the sequence of SP whistler components is due to a wave traveling back and forth along the same path. We suggest that the multiple traces of an SP whistler are due to wave packets which enter the ionosphere at various latitudes and travel along different paths before reaching the satellite. This is illustrated schematically in Figure 3, which shows wave packets entering the ionosphere at latitudes A, B, C, and D. The packets originate in a single lightning stroke on the ground at point O and reach the satellite S by the different paths shown. We found by tracing rays that horizontal gradients are needed only for the first reflection of an SP whistler component around 1000 km. Vertical gradients alone can keep the ray reflecting back and forth roughly between 100 km and 1000 km [*Smith et al.*, 1966]. When this model is used, the absence of any particular SP whistler component can be explained by the absence of horizontal gradients at the latitude where the component entered the ionosphere. The disappearance of SP whistler components at lower latitudes is due to the absence of horizontal gradients at these latitudes.

This research began as an attempt to explain the rising tone

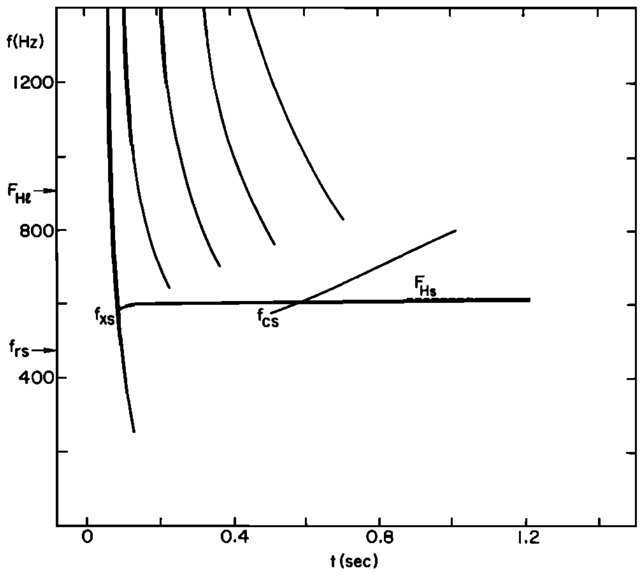

Fig. 1. Sketch of an SP whistler (with several components), a proton whistler, and a riser, all originating from the same lightning stroke at $t = 0$. The frequencies and propagation times are typical for mid-latitudes and for satellite altitudes around 1000 km. Here F_{Hl} and F_{Hs} stand for the proton gyrofrequencies at the bottom of the ionosphere and at the satellite location, respectively, and f_{rs}, f_{cs}, and f_{xs} are the two-ion resonant, the ion cutoff, and the crossover frequencies at the satellite location, respectively.

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[1] Summary and entire article are available on microfiche. Order from American Geophysical Union, 1909 K Street, N.W., Washington, D. C. 20006. Document J75-014; $1.00. Payment must accompany order.

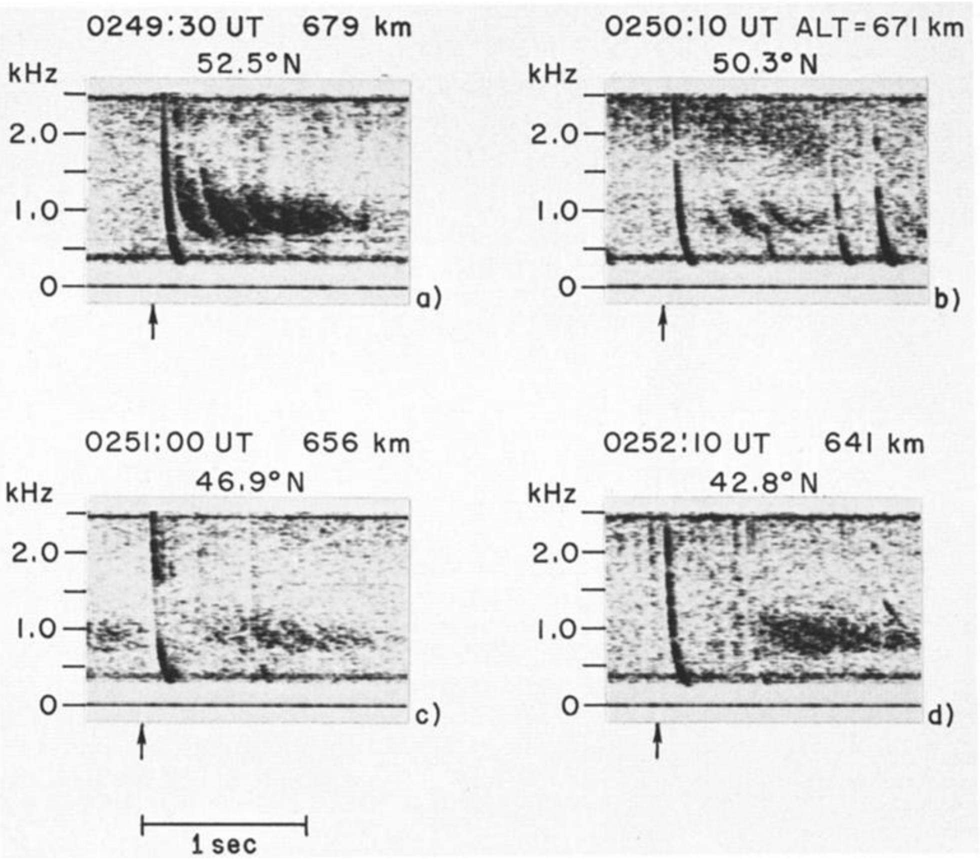

Fig. 2. Spectrogram records of SP whistlers received on the Ogo 4 satellite, October 17, 1967. The dipole latitude and altitude of the satellite are shown above each record. The variation in intensity of the various components as a function of latitude is apparent. As the satellite moves to lower latitudes, the components following the initial trace disappear in succession. The arrows indicate the approximate time of origin of each SP whistler event. The horizontal line at the top and the cutoff near 300 Hz are of instrumental origin.

originating near the proton whistler in Figure 1. The noise tone originates roughly 400 ms after the first appearance of the SP whistler and rises in frequency from 580 to 800 Hz over a period of 510 ms. The risers were usually detected at middle latitudes and at an altitude of about 900 km. They were always accompanied by SP whistlers and usually by proton whistlers. *Laaspere and Johnson* [1973] observed similar traces on Ogo 6 records and proposed that the rising tone was a new type of stimulated emission. This type of riser actually was first observed by *Carpenter et al.* [1964]. We found that the risers were similar in shape to the ion cutoff whistlers that were explained by *Muzzio* [1968] in terms of the reflection of downcoming VLF waves near the ion cutoff frequency. We conclude from tracing rays that the risers are propagation phenomena associated with the effect of the ion cutoff frequency on a downcoming SP whistler component and are in fact a new kind of ion cutoff whistler.

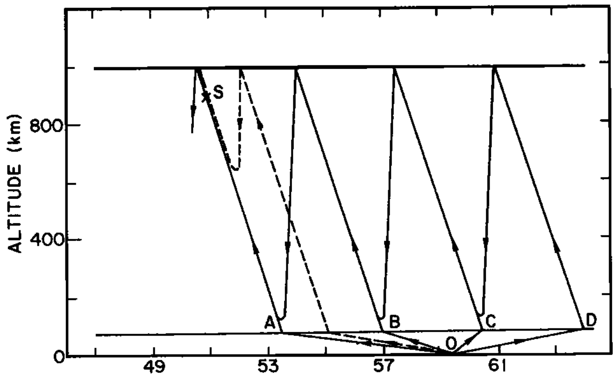

Fig. 3. Paths taken by different components of an SP whistler before reaching a satellite at position S. The first, second, third, and fourth components are produced by wave packets entering the lower ionosphere at A, B, C, and D, respectively. The waves originate in a lightning flash at O. The dashed line is the path of the riser. The figure is schematic and drawn for typical latitudes and altitudes.

The propagation path of the riser is shown by the dashed lines in Figure 3. Near the ion cutoff frequency the wave sees a rapid decrease in refractive index and is turned back upward and received by the satellite. Near the ion cutoff frequency the group velocity tends to zero [*Gurnett et al.*, 1965], and the turning around introduces a large time delay. A higher frequency wave has a larger time delay partly because it is reflected at a lower altitude and partly because the group velocity near the ion cutoff frequency decreases with altitude. Missing portions of SP whistler components in the frequency range of the riser entered either the riser mode or the proton whistler mode.

If the riser were indeed a stimulated emission, then theories which describe emissions as being generated near the magnetic equator would have to be seriously reconsidered. Our demonstration that the riser is a propagation phenomenon shows that in the interpretation of new types of magnetospheric noise, propagation effects deserve careful and early study. The SP whistlers and the associated riser also have the potential of developing into a diagnostic tool for probing electron and ion densities in the ionosphere.

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REFERENCES

Carpenter, D. L., N. Dunckel, and J. F. Walkup, A new very low frequency phenomenon: Whistlers trapped below the protonosphere, *J. Geophys. Res.*, *69*, 5009, 1964.

Gurnett, D. A., S. D. Shawhan, N. M. Brice, and R. L. Smith, Ion cyclotron whistlers, *J. Geophys. Res.*, *70*, 1665, 1965.

Kimura, I., Effects of ions on whistler-mode ray tracing, *Radio Sci.*, *1*, 269, 1966.

Laaspere, T., and W. C. Johnson, Additional results from an Ogo 6 experiment concerning ionospheric and electromagnetic fields in the range 20 Hz to 540 Hz, *J. Geophys. Res.*, *78*, 2926, 1973.

Muzzio, J. L. R., Ion cutoff whistlers, *J. Geophys. Res.*, *73*, 7526, 1968.

Smith, R. L., An explanation of subprotonospheric whistlers, *J. Geophys. Res.*, *69*, 5019, 1964.

Smith, R. L., I. Kimura, J. Vigneron, and J. Katsufrakis, Lower hybrid resonance noise and a new ionospheric duct, *J. Geophys. Res.*, *71*, 1925, 1966.

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