Reports

Ionospheric Effects on the Transmission of Ultralow-Frequency Plasma Waves

Abstract. *Measurements of magnetospheric ultralow-frequency plasma waves (period τ, $\sim$ 18 to 150 seconds) on the ground under continuous daylight conditions in the Antarctic and under alternate day-night solar illumination at the conjugate station in Quebec indicate a significant local time dependence in the transmission properties of the ionosphere for waves of these periods. When the Antarctic station is compared with the Quebec station, the tilt (with respect to the ionosphere) of the orientation plane of the waves is observed to be larger at local noon than at local night.*

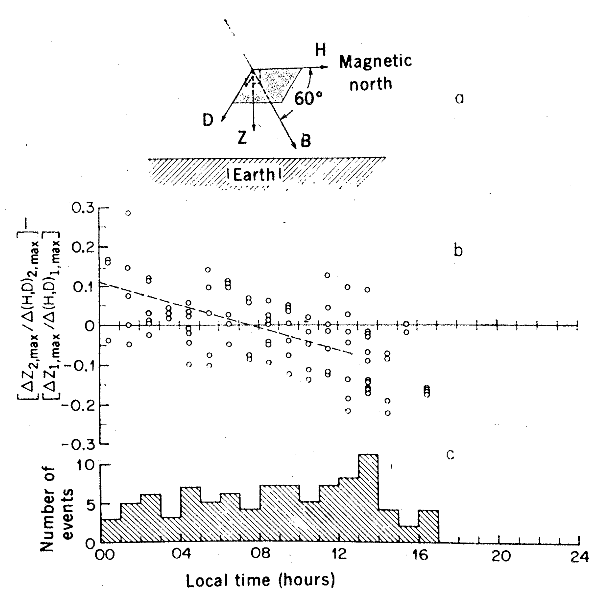
Reported here are quantitative observations and measurements of an ionospheric effect on the transmission of magnetospheric ultralow-frequency (ULF) (period τ, $\sim$ 18 to 150 seconds) plasma (hydromagnetic) waves to the ground. A comparison of the plane of orientation of the plasma waves measured at Siple Station, Antarctica, and at the conjugate point, Lac Rebours, Quebec, indicates a local time (LT) dependence in the relative orientation of the planes of the observed waves. Contrary to expectations, we have discovered that the major LT change in the wave orientations occurred in the waves detected at the Antarctic location. At the Antarctic station during the local nighttime hours, but under continuous 24-hour solar illumination, the component of the plasma wave directed perpendicular to the ionosphere (and ground plane) is smaller relative to the total wave vector than the same vertical component measured when the plasma wave is observed during daylight hours. Wave measurements at the Quebec station indicate no detectable LT effects on the wave transmission.

It is particularly important to study the propagation and transmission of such naturally occurring ULF waves if they are to be used eventually as tools for detailed diagnostics of the magnetospheric plasma environment (*1*). Sugiura (*2*) reported the first evidence of elliptically polarized, geophysical hydromagnetic waves in ground records of changes in the earth's field at College, Alaska. Evidence of $\sim$ 200-second waves in the magnetosphere was first reported from data obtained on an early Explorer satellite (*3*), and later, satellite-measured waves were associated with similar frequency variations observed at a ground station (*4*). In the only other study that we know of on the transmission of satellite-measured waves to the ground at these frequencies (*5*), it was found that a pure longitudinal wave (magnetic field perturbation along the direction of the local field intensity) observed in the magnetosphere at the equator was measured on the ground near the foot of the field line through the satellite as essentially a transverse wave (magnetic field perturbation perpendicular to the local field intensity), with only a small component directed along the magnetic field.

Fig. 1. (a) Orientation at Lac Rebours (station 2) of the measured components of the changes in the earth's magnetic field. At Siple Station (station 1), **Z** is directed upward. (b) Local time dependence of the difference in the plane of orientation of the plasma waves measured at the two conjugate stations. (c) Local time distribution of the analyzed plasma wave events.

Although the literature describing observations of plasma waves at the ground and on satellites in the magnetosphere has greatly expanded in recent years (*6*), the difficulty of making simultaneous satellite-ground comparisons is quite formidable since a spacecraft is generally in motion relative to a fixed ground station. An alternative, but not equivalent, method is to study plasma waves observed simultaneously at two ground stations which are close to opposite ends of the same magnetic field line (conjugate stations).

We obtained the plasma wave results reported here by using identically instrumented three-component ground-based flux-gate magnetometer stations at conjugate points near the $L = 4$ magnetic field line (at $\sim$ 4°W geomagnetic longitude). The three orthogonal components of the total vector field **B** (Fig. 1a) at each station were digitized at 2-second intervals and written in computer-compatible format on magnetic tape. The noise level of each detector system was ~ 0.2 gamma over the bandwidth considered here (1 gamma $\equiv 10^{-5}$ gauss). Further details of the instrumentation will be published elsewhere (*7*). The station in the Northern Hemisphere (station 2), at Lac Rebours, Quebec, is located within 30 km of the calculated conjugate point of the station in the Southern Hemisphere at Siple Station, Antarctica (station 1) (*8*). The stations are within 1 hour of the same LT. This is one of the most closely conjugate pairs of ground stations yet established for the study of magnetospheric processes and, since both stations are at $L \sim 4$, the conjugacy is affected only slightly by the distorted



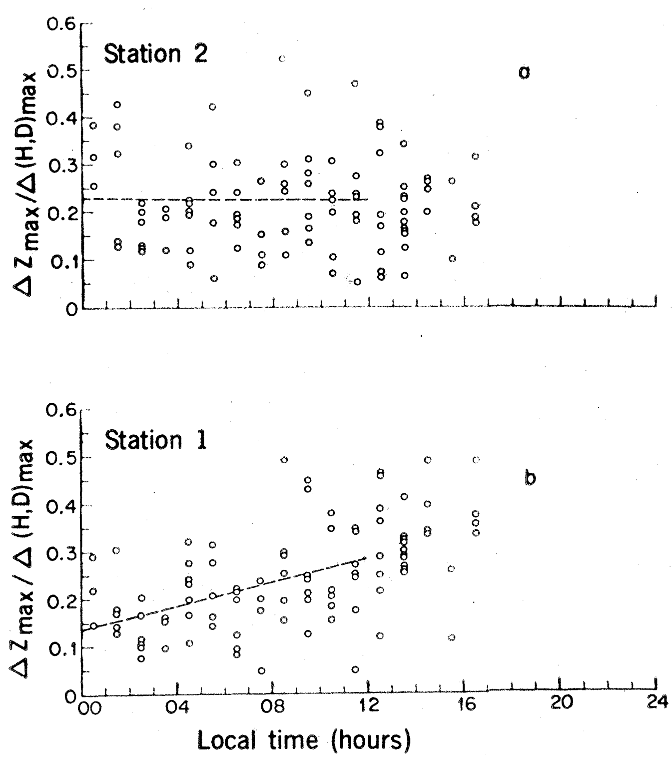
magnetosphere or higher-latitude auroral currents (*8, 9*). The data presented here were obtained between 14 December and 24 January during the 1970–1971 Antarctic austral summer when Siple Station was under continuous daylight conditions and sunrise occurred at 100 km altitude over Lac Rebours at ~ 0700 LT.

Since naturally occurring ULF plasma waves of magnetospheric origin are used as the ionospheric probing signals, it is necessary to ensure that the same waves are being observed at both stations. By computer processing, frequencies of period > 240 seconds were removed from each component of the vector field measurements at each station. Graphs of the resulting digitized vector components of the detected plasma waves (generally a few gammas in amplitude) measured at the conjugate stations during moderately quiet magnetic conditions (3-hour average geomagnetic index $K_p \leqq 3$) were scanned visually for evidence of coincident, quasi-sinusoidal ($\tau \sim 18$ to 150 seconds) variations. By means of both visual inspection and power spectral analyses, nonmonochromatic waves ($\Delta\tau/\tau > 10$ percent) were rejected. The remaining events were further processed by narrow bandwidth filtering at a frequency and bandwidth determined from the power spectra. The filtered wave components were then used to compute the total vector amplitude and wave ellipticity ε (ratio of the minor axis of the wave ellipse to the major axis of the wave ellipse) in the plane of the wave. Waves at the two stations with maximum amplitudes occurring in different cycles or waves with maximum amplitudes differing by more than 50 percent, or both, were rejected. Also rejected were waves whose major axis changed orientation with respect to the fixed field line or whose ellipticity variations $\Delta\varepsilon$ during an event were $> \pm 0.1$ around the maximum cycle at either station. Out of ~ 300 initial events, imposition of the selection criteria left 94 accepted events distributed in LT between local midnight and 1700 LT (Fig. 1c). Essentially no wave events were found between ~ 1700 and ~ 2400 LT (*10*).

An effect that is expected to occur for a wave incident on the surface of a uniform conductor of large horizontal extent (for example, the ionosphere, the earth's crust, or the ocean surface) is a reduction in the amplitude of the vertical wave component ΔZ relative to the amplitude of the horizontal component $\Delta(H,D)$ [$\Delta(H,D) \equiv (\Delta H^2 + \Delta D^2)^{1/2}$]. This magnetic effect arises from the currents induced in the conductor by the incident wave. We compared the relative wave orientation at maximum intensity for each event measured at each conjugate station directly by computing for each event the tangent of the vertical Parkinson angle (*11*) θ defined here as

$$\tan\theta = \frac{\Delta Z_{\max}}{\Delta(H,D)_{\max}}$$

The local time dependence of the difference between $\tan\theta_2$ and $\tan\theta_1$ (for Lac Rebours and Siple Station, respectively) for each event is shown in Fig. 1b. This comparison of the wave orientations at the two stations, which minimizes the effects of possible systematic source changes, indicates a clear LT dependence in the relative wave



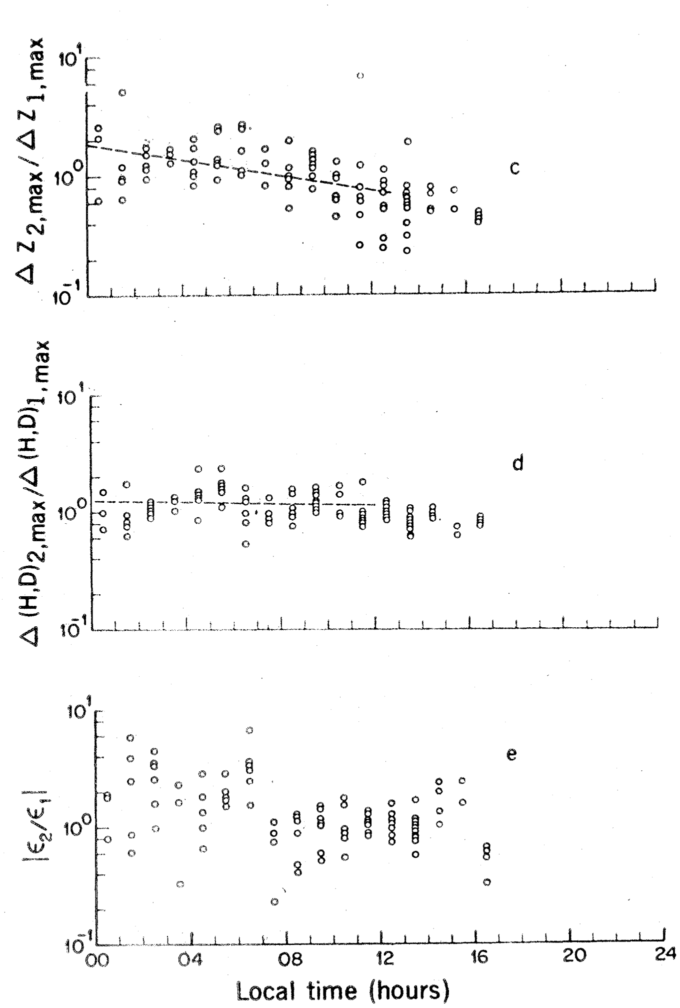


Fig. 2. (a) Local time dependence of the relative magnitude of the Z component to the horizontal-plane component of the plasma waves measured at Lac Rebours. (b) Same as in (a) for Siple Station. (c) Local time dependence of the ratios of the vertical components of the plasma waves measured at the conjugate station. (d) Local time dependence of the ratios of the horizontal components of the plasma waves measured at the conjugate stations. (e) Local time dependence of the ratios of the ellipticities of the plasma waves as measured at the conjugate stations.

orientations. A linear least-squares fit made to the data between 0000 and 1300 LT gives an indication of the reliability of the observed LT dependence. The correlation coefficient of the fit (-0.64) indicates a probability $P < 1$ in 10^5 for a chance occurrence of the systematic LT change. The t-test on the correlation coefficient indicates a $P < 1$ in 10^5 for the null hypothesis to be correct. (The linear fit was made only to the first 13 hours. Although it is likely that the LT dependence being studied is a periodic function, roughly symmetrical about local noon and midnight, the absence of local evening events prevented the use of a more sophisticated fitting function such as a sinusoid, whose phase could also be varied. However, the data presented here do not give evidence for a change in $\tan \theta$ after local noon.) The LT change observed in the relative orientations of the magnetospheric plasma waves measured at the conjugate stations can be attributed to changes in the ionospheric transmission of these waves at different local times.

Graphs of the functions $\tan \theta_2$ and $\tan \theta_1$ for Lac Rebours and Siple Station, respectively, plotted individually as a function of LT in Fig. 2, a and b, indicate a significant increase in $\tan \theta_1$ at local noon over that at local midnight. Little variation is observed in $\tan \theta_2$ with LT. The correlation coefficient (0.43) for the linear least-squares fit through the data observed at Siple Station (Fig. 2b) indicates a $P < 1$ in 10^4 for a chance occurrence of the systematic LT change. The ratios $\Delta Z_{2,\max}/\Delta Z_{1,\max}$ and $\Delta(H,D)_{2,\max}/\Delta(H,D)_{1,\max}$ plotted in Fig. 2, c and d, indicate that the predominant LT change measured in the plasma waves at Siple Station occurs essentially entirely in the Z component. On the basis of the results in Fig. 2b, the data of Fig. 2c indicate that a larger relative Z component is measured at Siple Station during local day than during local night. The correlation coefficient (-0.56) for the least-squares fit through the data of Fig. 2c indicates a $P < 1$ in 10^5 for a chance occurrence of the observed LT dependence. The correlation coefficients for the data of Fig. 2, a and d, are -0.02 and -0.08, respectively.

The comparison of the plasma wave orientations at the conjugate stations (Fig. 1b) suggests a LT dependence in the ionospheric transmission of these waves to the ground stations in the Northern Hemisphere and Southern Hemisphere. Although a LT change in the localization of the plasma wave source in the magnetosphere could produce a systematic change on the ground (*12*), the comparison of the conjugate data should minimize the effects of any such change. Although changes are observed in the ratios of the wave ellipticities $\varepsilon_2/\varepsilon_1$ at the two stations (Fig. 2e), these ratios do not have the same LT dependence as the results shown in Fig. 1b.

The large Hall conductivity in the E region during daylight (*13*) ($\sim 6 \cdot 10^{-15}$ abmho/cm) is qualitatively considered to most affect the transmission of these ULF waves (*14*). Although the undisturbed conductivity in the E region can decrease to a value of $\sim 10^{-16}$ abmho/cm under nighttime conditions (*13*), it is common for large E-region conductivities and gradients to occur during nighttime hours (some such effects are due to large sporadic E layers). Because it is impossible to separate source, ionospheric, and possible ground effects (such as subsurface directional conductivity anomalies) from the measurements of $\tan \theta$ made at the individual stations, these data cannot be used to draw definitive conclusions about whether the ionosphere over the Northern Hemisphere or the ionosphere over the Southern Hemisphere is exerting the greatest effect on the wave transmission. However, if the results of Fig. 2, a and b, are interpreted as due to purely ionospheric conditions, then the data suggest that, on the average, the local night, daylit ionosphere over the Antarctic station ($L \sim 4$) has enhanced densities or density gradients, or both (probably in the E region), that affect ULF wave transmission during the local night hours (Fig. 2b). The results from the northern conjugate station (Fig. 2a) suggest that, on the average, the density gradients and densities in the nighttime (probably E region) ionosphere are such that ULF wave transmission is the same under both light and dark ionospheric conditions.

Such effects could possibly be produced by two causes. First, the $L = 4$ field line at the longitude of the station is characterized by a large north-south hemispheric asymmetry of the altitudes at which particle-mirroring occurs, and hence an asymmetry will exist in the particle precipitation. Particles mirroring at an altitude of ~ 320 km over Lac Rebours would mirror at ~ 100 km over Siple Station and would be lost. Hence, any magnetospheric wave-particle pitch-angle scattering mechanism would produce more precipitation, and hence more ionization, over Siple Station than over Lac Rebours. Second, the fact that the stations are closer during local night hours than during local day hours to the region (auroral oval) where particles precipitate may produce an important LT effect in particle precipitation into the ionosphere at both stations. The asymmetry of particle-mirroring altitudes is probably of great importance in producing nonconjugate ionospheric ionization over the two stations. A possible longitudinal dependence of particle precipitation in the auroral zones has recently been discussed (*15*).

Little published information exists on the conditions of the local night Antarctic E-region ionosphere at geomagnetic latitudes $\sim 60°$, under continuous daylight conditions. Results from a study of the F2 region at the SANAE (South African National Antarctic Expedition) base in the Antarctic ($L \sim 4$; 44.2°E geomagnetic longitude) suggest that particle precipitation contributes significantly to disturbance conditions measured there (*16*). (Possible LT dependencies of the disturbances were not considered.) It is clear from the results presented here that correlated studies should be carried out of simultaneous measurements of E-region density profiles and characteristics of ULF plasma waves at the conjugate points. Plasma wave measurements made during the equinoxes and the summer solstice would extend the study reported here to dark Antarctic ionospheric conditions at different local times.

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10. The disappearance (often quite suddenly) of monochromatic plasma waves in the local afternoon-evening sector of the magnetosphere is quite striking in the data. This observation is consistent with some previous

statistical studies [J. A. Jacobs (6); ——— and K. Sinno, *J. Geophys. Res.* **65**, 107 (1960)] and may be of extreme importance in an ultimate understanding of the plasma wave source mechanism.
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14. Little theoretical work has been done on the transmission of these frequency waves. In contrast to the finite-layered ionosphere models sufficient for studying the transmission of waves with frequencies > 1 hertz [C. Greifinger and P. Greifinger, *J. Geophys. Res.* **70**, 2217 (1965); E. C. Field and C. Greifinger, *ibid.*, p. 4885; *ibid.* **71**, 3228 (1966)] a full-wave solution is needed for the plasma waves considered here, whose wavelengths are of the order of several earth radii. Recently, significant progress has been made in the direction of a full-wave solution with the use of a daytime ionosphere model (*12*).
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Sandstone: Secular Trends in Lithology in Southwestern Montana

Abstract. *Long-term secular trends in the composition and texture of sandstones in southwestern Montana reflect changing provenance and depositional environment, which in turn reflect changing tectonic patterns in the Cordilleran mobile belt just to the west.*

The stratigraphic column at the northern end of the Tobacco Root Mountains in southwestern Montana is a diverse sequence of detrital, chemical, and volcanic rocks deposited on the eastern flank of the Cordilleran mobile belt during Paleozoic, Mesozoic, and Cenozoic eras of geologic time. Its total thickness of 4200 m is divided about equally among the three eras. Several large gaps appear in the stratigraphic record, notably, Ordovician through Middle Devonian and Middle Triassic through Middle Jurassic. Rock units corresponding to these time intervals either were never deposited in this area, or were eroded prior to deposition of the overlying units. The column is not uniform from bottom to top; rather, each erathem (*1*) is broadly characterized by a distinct assemblage of lithologic types. The strongest secular contrasts occur in the sandstones. This report describes long-term trends, both compositional and textural, in sandstone lithology in the column, and relates these trends to tectonic evolution of the Cordilleran mobile belt.

In general, the composition of sandstones is controlled by provenance, that is, the character of the source area, where detritus is generated. The texture is controlled largely by the environment in which deposition of the detritus takes place, but is not totally independent of provenance. Provenance and depositional environment are in turn controlled by the character and intensity of tectonism, that is, deformation of the earth's crust, both in the source area and at the depositional site.

Composition and texture are frequently described in terms of maturity. A sandstone having a high content of well-rounded, well-sorted quartz, and a correspondingly low content of unstable materials, such as feldspars and lithic fragments, is mature. Besides quartz, other relatively indestructible minerals, such as zircon, tourmaline, and rutile, may be present in small quantities. (These and other so-called heavy minerals, although of diminutive

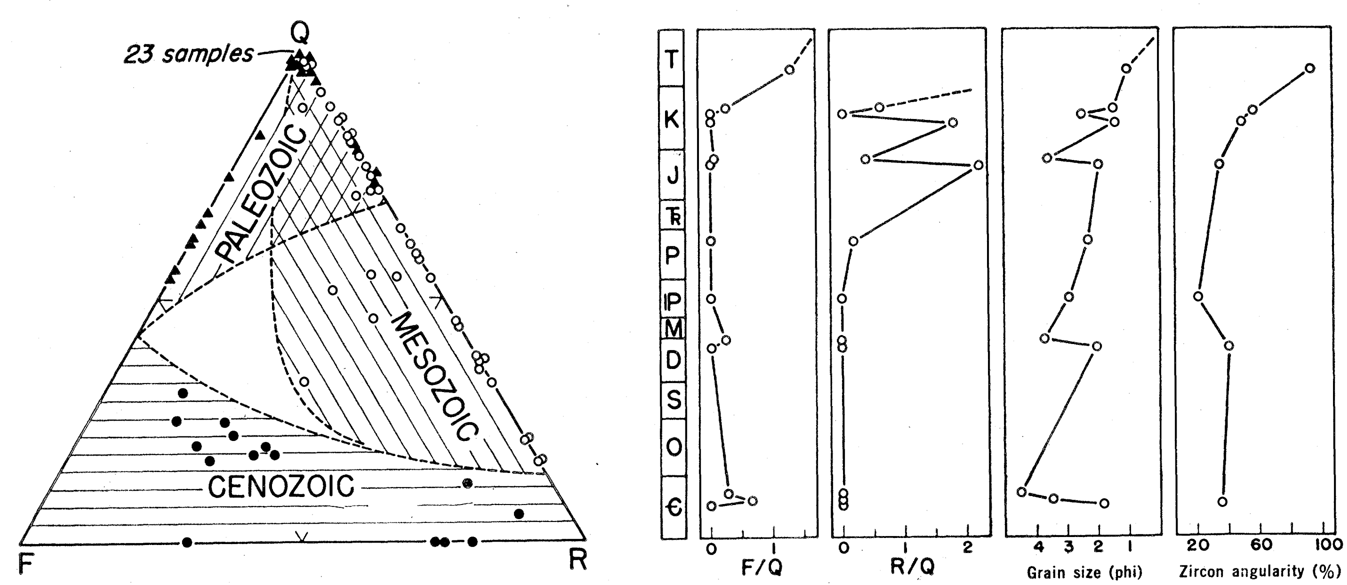

Fig. 1. Composition of 105 sandstones from the study area according to Folk's ternary classification (*2*). The poles of the ternary diagram are quartz (*Q*); feldspars and feldspathic rock fragments (*F*); and all other rock fragments, including chert (*R*). Paleozoic samples (triangles) are concentrated near the *Q* pole, Mesozoic samples (open circles) along the *Q-R* edge, and Cenozoic samples (black circles) along the *R-F* edge of the triangle. Note that one point at the *Q* pole of the ternary diagram represents 23 Paleozoic samples. The Paleozoic and Mesozoic fields overlap because of a gradual transition in sandstone composition from late Paleozoic to Mesozoic time. (All the Permian samples and most of the Jurassic samples are contained within this overlap.) At the right, certain compositional and textural properties of the sandstones are averaged over major rock units and plotted against time, on a scale ranging from Cambrian through Tertiary. The feldspar/quartz ratio, rock fragment/quartz ratio, mean grain size, and zircon angularity increase in younger sandstones.