

Evidence of Drift Waves at the Plasmopause

PAUL M. KINTNER AND DONALD A. GURNETT

Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242

As the Hawkeye 1 spacecraft crosses the plasmopause at high altitudes ($R > 3 R_E$), a band of electric field noise is often detected in the frequency channels from 1.7 to 178 Hz. No corresponding magnetic field noise is detected, indicating that the noise is electrostatic (or at least quasi-electrostatic), and the electric field is polarized perpendicular to the plasma density gradient. The noise is only detected when the scale length of the plasmopause is $0.1 R_E$ or less, indicating that a large density gradient is required to produce the noise. These characteristics are all consistent with the interpretation that this noise consists of electrostatic waves excited by the drift mode instability. By using reasonable assumptions concerning the wavelengths of these waves the observed frequency spectrum can be explained as being due to Doppler shifts caused by spacecraft motion through the plasma.

INTRODUCTION

Gradients within a magnetized plasma of density or temperature produce particle drifts which, if sufficiently strong, are both unstable and capable of supporting very low phase velocity electrostatic drift waves propagating perpendicular to the magnetic field and perpendicular to the gradient. Although the drift wave instability was first analyzed for laboratory plasma, drift wave instabilities in space plasmas have also received some attention [Lui, 1970; Wu, 1971; LaQuey, 1973], especially with regard to understanding micropulsations [Swift, 1967; D'Angelo, 1969; Coroniti and Kennel, 1970].

One of the more likely regions of the magnetosphere to exhibit the drift wave instability is the density gradient in the low-energy thermal plasma at the plasmopause, where during periods of large Kp or just after them the e folding distance of the density gradient is frequently less than $0.1 R_E$ [Chappell *et al.*, 1970]. Hasegawa [1971] and Kikuchi [1971] have investigated the plasmopause density gradient and concluded that not only could reasonable growth rates exist but because of finite β effects ($\beta \approx m_e/m_i$) the instability couples to both the shear Alfvén wave and the ion acoustic wave in the direction of the ambient magnetic field. The shear Alfvén wave is capable of producing micropulsations observable on the ground, and Kikuchi and Taylor [1972] have shown that Pc 1 micropulsations are frequently observed on the ground near the same latitude and local time as Ogo 3 when it observes a structured plasmopause with sharp density gradients.

Despite the interest in the drift wave instability, very little *in situ* evidence has been presented for its existence in space plasmas. The purpose of this paper is to report on the existence of electrostatic ELF waves found only at the plasmopause and to demonstrate that their polarization and spatial relationship to the plasmopause density gradient are consistent with a drift wave origin. The data presented here come from the VLF electric field plasma wave experiment on board the Hawkeye 1 satellite, which has been previously described by Kurth *et al.* [1975]. The antenna for the experiment consists of a single cylindrical dipole whose length from center to center of the exposed elements is 36 m.

OBSERVATIONS

Hawkeye 1 is in a highly elliptical polar orbit with perigee over the south pole and apogee near $21 R_E$ over the north pole. During each orbit it passes through the high-altitude plasmopause twice. Figure 1 illustrates two passages through the

plasmopause, one on January 18, 1975, and one on February 19, 1975. The $L = 4$ field line is indicated, and for both cases the plasmopause lies between $L = 4$ and $L = 4.5$. These two dates are chosen as representative examples which contain electrostatic noise at the plasmopause, which is believed to be associated with the drift wave instability.

The plasmopause is easily identified from the plasma wave data. The spectrogram for January 18, 1975, is presented in Figure 2 and shows the output of 16 electric field channels ranging in frequency from 1.78 Hz to 178 kHz and 6 magnetic field channels ranging from 1.78 to 562 Hz. The dynamic range of each channel is 100 dB. To order the data, the time (in UT), the L shell, the radial distance, and the magnetic local time are given every 10 min. Between 1240 and 1258 UT, electromagnetic (em) radiation trapped above the local plasma frequency is present in the 17.8-, 23.7-, and 31.1-kHz channels. This radiation cuts off at the local plasma frequency and provides a convenient measure of the local plasma density [Gurnett and Shaw, 1973]. Just following the trapped electromagnetic radiation cutoff, UHR waves ($f_{UHR} = (f_p^2 + f_g^2)^{1/2}$) are present in the 42.2-, 56.2-, 100-, and 178-kHz channels. These waves are common features of the plasmopause [Shaw and Gurnett, 1972], and since $f_g^2 \ll f_p^2$, the UHR waves are close (within 20%) to the local plasma frequency. Together the trapped radiation and UHR waves delineate the plasmopause, and the local density at any point on the $f = f_{pe}$ line can be deduced from the expression $n_e = (f_{pe}/9 \text{ kHz})^2$, in electrons per cubic centimeter.

An additional diagnostic of the plasmopause is the sudden appearance of plasmaspheric hiss in the 178-Hz through 5.62-kHz channels at about 1300 UT. Plasmaspheric hiss is thought to be generated within the plasmasphere [Thorne *et al.*, 1974], and most ray paths are reflected at the low-latitude plasmopause (for example, see Muzzio and Angerami [1972]). The sharp onset of the plasmaspheric hiss at about 1300 UT supports the identification of the plasmopause location obtained by examination of trapped em radiation and UHR waves. The Kp index for this 3-hour period is 4+, and since the plasmopause narrows for larger Kp [Chappell *et al.*, 1970], the sharp transition is consistent with the expected Kp dependence.

From 1254 to 1259 UT the 1.78- through 178-Hz channels indicate a signal which corresponds almost exactly with the electron density gradient of the plasmopause. Examination of the magnetic search coil record for this period shows that no signal is present in the low-frequency channels from 1250 to 1300 UT, and hence this noise is most likely electrostatic. Detailed comparisons at 17.8 Hz show that the ratio of the

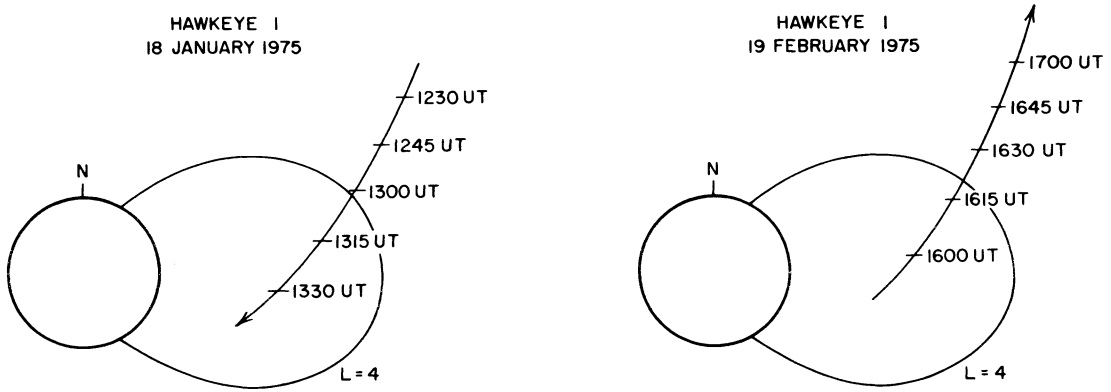


Fig. 1. Trajectories of Hawkeye 1 near the plasmapause on January 18 and February 19, 1975.

electric to the magnetic field energy density exceeds 10^{-3} . Since the ratio of electric to magnetic energy density for a whistler wave is anticipated to be less than 10^{-5} , these results illustrate the electrostatic (or at least quasi-electrostatic) character of the waves. Since the maximum intensity occurs in the region of maximum density gradient and therefore maximum diamagnetic drift velocity, this noise is tentatively identified as drift waves.

A second example of drift waves is shown in the spectrogram of Figure 3. This spectrogram is in the same format as

Figure 2. The trapped em radiation and UHR waves are again clearly evident and indicate the local electron plasma frequency. Plasmaspheric hiss is present from 178 Hz to 5.62 kHz and terminates, as is anticipated from the $f = f_{pe}$ line, at 1625 UT. The continuation of the 562-Hz channel beyond 1625 UT is produced by a narrow band emission. The drift waves in this case are present from 1620 to 1626 UT in the 5.62- through 56.2-Hz channels. The drift waves may also be present in the 178-Hz channel but cannot be easily separated from the plasmaspheric hiss.

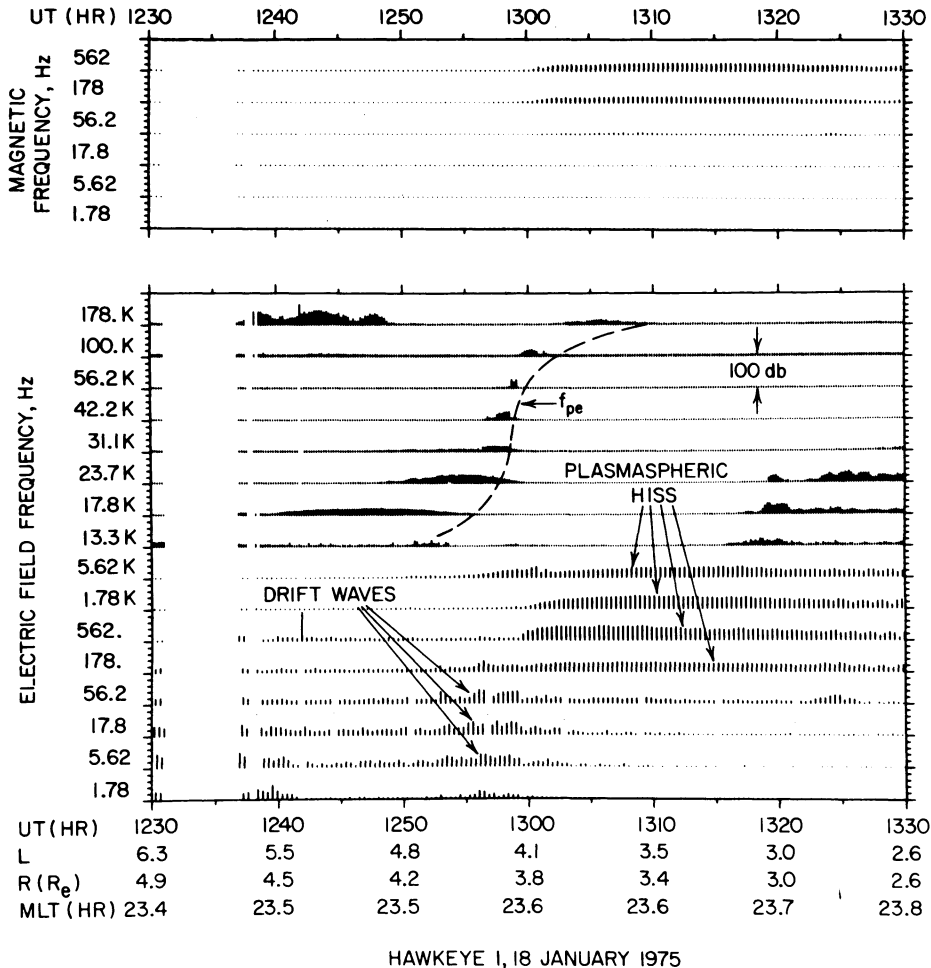
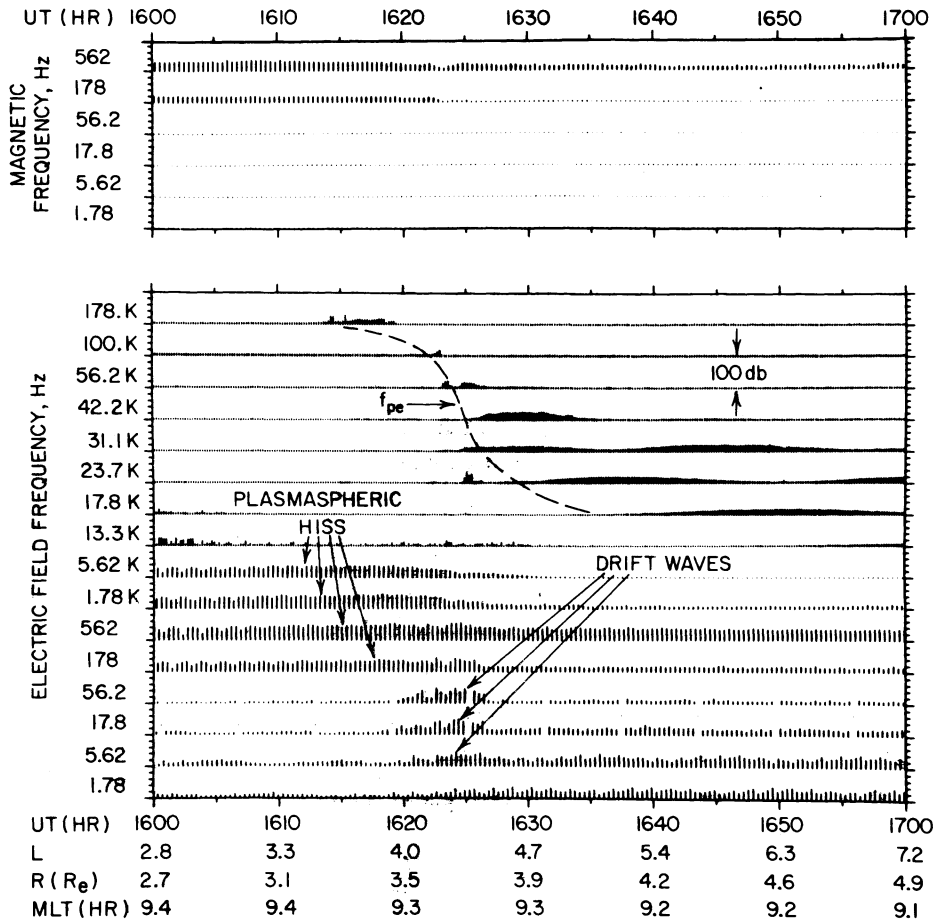


Fig. 2. Electric field spectrogram showing the output of the 16 electric field channels from 1.78 to 178 kHz and 6 magnetic field channels from 1.78 to 562 Hz for January 18, 1975.



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Fig. 3. Same format as Figure 2 for February 19, 1975.

This second example of February 19, 1975, is at a magnetic local time 10 hours later than the first example and serves to show that the drift waves are not confined to a particular local time. Comparable drift waves are present on about one of every five orbits and are only observed when the e folding distance of the plasmapause density gradient is less than $0.1 R_E$. The drift waves are found at all local times, although the number of examples collected is insufficient to claim that there are no local time effects.

The spectral properties of the drift waves are presented in Figure 4 in a calibrated spectrogram from 1 Hz to 1 kHz. Three spectrums, measured consecutively, are illustrated for the time period 1255–1256 UT during which the noise attained its maximum intensity on January 18, 1975. This time is chosen because plasmaspheric hiss is not present, and hence the drift wave spectrum can be examined without contamination. The spectrum is definitely not a simple power law and exhibits several interesting features. Between 5.6 and 56 Hz there is a plateau in the spectrum. Above 56 Hz the spectrum decreases suddenly as an approximate power law whose index is smaller than -1 . The break in the spectrum above 56 Hz can be understood if one accepts the view that the noise has a very slow phase velocity compared with the spacecraft velocity of 5 km/s. The antenna then responds to the power distribution in wave number space, and the potential difference between the antenna probes may be written as

$$\Delta\varphi = dE(k) \frac{\sin kd}{kd} \quad k = 2\pi/\lambda$$

where d is the antenna length and $E(k)$ is the electric field amplitude associated with wave vector k . The breakpoint of this spectrum, if it is assumed that $E(k)$ is flat, occurs at $kd = \pi$ or, for a spacecraft velocity of 5 km/s, at a frequency of 84 Hz, which agrees quite well with the break in the spectrum of Figure 4. Since the spectrum falls off faster than $1/k$ above 56 Hz, $E(k)$ is most likely not flat above 56 Hz.

The electric vector associated with a drift wave perturbation is primarily directed perpendicular to both the local magnetic field and the density gradient. The only situation in which Hawkeye 1 can distinguish between waves ordered by the magnetic field and waves ordered by the density gradient occurs when the spin axis is parallel to the local magnetic field. In this case the antenna is always perpendicular to the magnetic field, and all orientations with respect to the density gradient or L shell surface are sampled.

During the electrostatic noise event of January 18, 1975, the Hawkeye 1 spin axis was located within 10° of the magnetic field. To examine polarization, Figure 5 contains wide band data from Hawkeye for the time period 1258:00–1259:00 UT. A high-pass filter on the transmitter cuts off frequencies below 100 Hz, but the high-frequency tail of the noise extends to 300 Hz. The spacecraft spin period is 10.88 s, and the noise is clearly modulated at half of the spin period. Since the antenna axis is almost exactly perpendicular to the magnetic field through the entire rotation, this modulation cannot be caused by the magnetic field. The arrows correspond to times when the antenna lies on an L shell surface and is perpendicular to

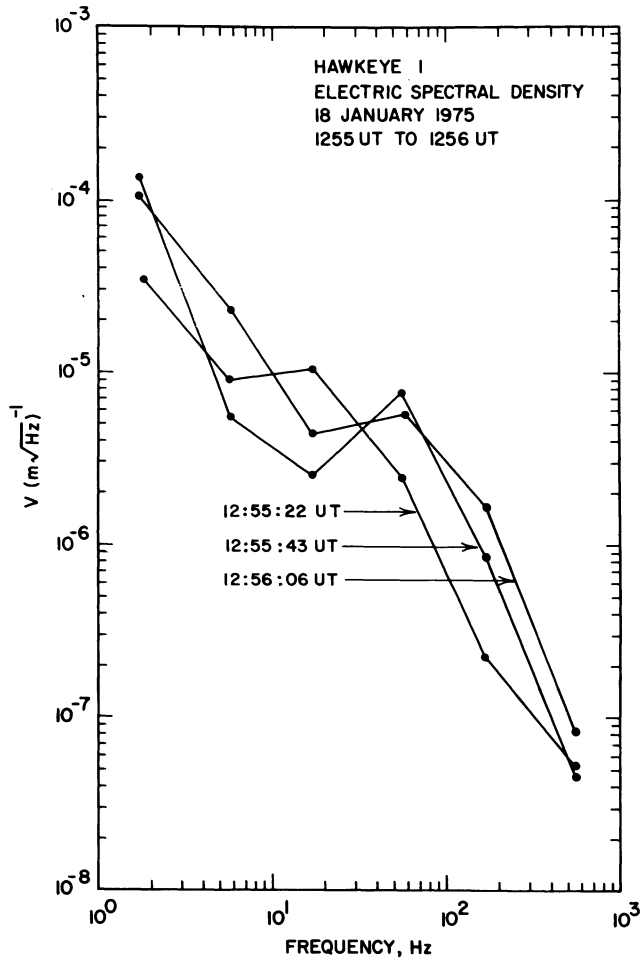


Fig. 4. Electric spectral densities for three consecutive spectral scans from 1255 to 1256 UT on January 18, 1975.

the density gradient. Midway between each arrow the antenna is perpendicular to the L shell surface and parallel to the density gradient. The electric field is seen to be closely polarized perpendicular to the plasma density gradient at the plasmopause.

The electric power is also not solely confined to the direction perpendicular to the density gradient, as can be seen from Figure 5. *Krall and Rosenbluth* [1963] have investigated the drift wave instability by allowing a component of the perturbation electric field (E_1) to be parallel to the density gradient. Taking the magnetic field in the \hat{z} direction and the density gradient to be in the x direction, they calculated the relation

$$\partial E_{1y}/\partial x \sim kE_{1x}$$

If the wave phase velocity is slow in comparison with the spacecraft velocity, the relation can be rewritten for the spacecraft reference frame as

$$E_{1y}/E_{1x} \sim fL_n$$

where L_n is the density gradient scale length. This implies that the degree of polarization with respect to the density gradient is dependent on the frequency. Careful examination of Figure 5 shows that the spin modulation increases with frequency as anticipated. At 100 Hz, very little polarization is apparent, while above 200 Hz the polarization is easily distinguished.

DISCUSSION

The drift wave instability has been analyzed by a number of authors for uniform fields and Maxwellian plasma [*Krall*, 1968; *Rosenbluth*, 1965; *Mikhailovskii*, 1967]. The discussion presented here will closely follow *Mikhailovskii's* results, since he recognized that for finite β ($\beta \gtrsim m_e/m_i$) the instability couples to both the ion acoustic and the shear Alfvén wave in the direction of the local magnetic field. At the plasmopause ($n_{H^+} = 500/\text{cm}^3$, $B = 600 \gamma$, $T_i = 1 \text{ eV}$), β is within 20% of m_e/m_i . The magnetic field is given by $\mathbf{B} = B_0\hat{z}$, the density gradient is in the x direction, and low frequency is assumed ($\omega < \omega_{ci}$).

The flute mode drift wave is specified by $k_z = 0$. The phase velocity of the wave in the y direction then is given by $\omega/k_y = v_d$, where $v_d = \rho_i v_{i,th}(1/n)[dn(x)/dx]$ and ρ_i is the ion gyro-radius. At the plasmopause, $(1/n)(dn/dx)$ is, for the two cases presented here, about $0.1 R_E$, which corresponds to $v_d = 2 \text{ m/s}$ for the above parameters.

If k_z is not zero, four new modes are introduced. Propagation in the y direction remains unaffected, but in the z direction an accelerated and retarded ion acoustic wave and an accelerated and retarded shear Alfvén wave are introduced. The ion acoustic velocity is about 10 km/s, and the Alfvén velocity is about 10^3 km/s . For low frequencies ($\omega \ll \omega_{ci}$) the spacecraft is unable to Doppler shift the ion acoustic or shear Alfvén modes to a frequency sufficiently high to be observed by the receiver. The slow drift wave mode though would be completely Doppler shifted by the spacecraft. In this case the receiver observes the mode in wave number space if there is power at sufficiently short wavelengths.

The drift wave spectrum may be estimated by calculating long and short wavelength cutoffs. At long wavelengths the field line length specifies a minimum k_z which at the plasmopause is about $2\pi/5 \times 10^8 \text{ km}$. For minimal Landau damping the parallel phase velocity is bracketed by $v_{i,th} \ll \omega/k_z \ll v_{e,th}$ or $\omega/k_z \approx 70 \text{ km/s}$. This implies that $k_z/k_y \approx 3 \times 10^{-5}$, and hence if the maximum λ_z is 50,000 km, the longest drift wavelength is 1.5 km. This assumes, of course, that by damping the parallel mode the drift wave mode is also damped. If this assumption is incorrect, even longer drift wavelengths may occur. Toward the short wavelength portion of the spectrum the growth rate continues to increase until $\rho_i/\lambda_y = \beta m_i/m_e \approx 1$. For shorter wavelengths the finite ion gyroradius damps the drift wave [*Rosenbluth et al.*, 1962] and quenches the instability. The spectrum should decay rapidly for wavelengths shorter than $\rho_i \approx 170 \text{ m}$. In the spacecraft reference frame the upper and lower wavelength cutoffs correspond to 3 and 30 Hz. The high-frequency cutoff should be observable, and the spectrum in Figure 4 shows a cutoff beginning between 56 and 176 Hz. As the filters are quite broad, the 56-Hz filter may be responding to a signal at 30 Hz, or the ion temperature may be cooler than assumed. Above 34 Hz the spectral shape is partially produced by the finite antenna length, but it can only account for a spectral index of -1 . As the spectrum decreases considerably faster than k^{-1} , the noise spectrum is most likely decreasing rapidly as well.

The maximum growth rate for the drift wave instability is

$$\gamma = \frac{v_{i,th}}{4(\pi)^{1/2}} \frac{1}{n} \frac{dn}{dx}$$

and for a density gradient of $0.1 R_E$ the growth rate is $2.3 \times 10^{-3} \text{ Hz}$. The growth rate is a maximum for wavelengths near $\lambda_y/\rho_i \lesssim \beta(m_i/m_e) \approx 1$. Since $\rho_i \approx 170 \text{ m}$, the spectrum should

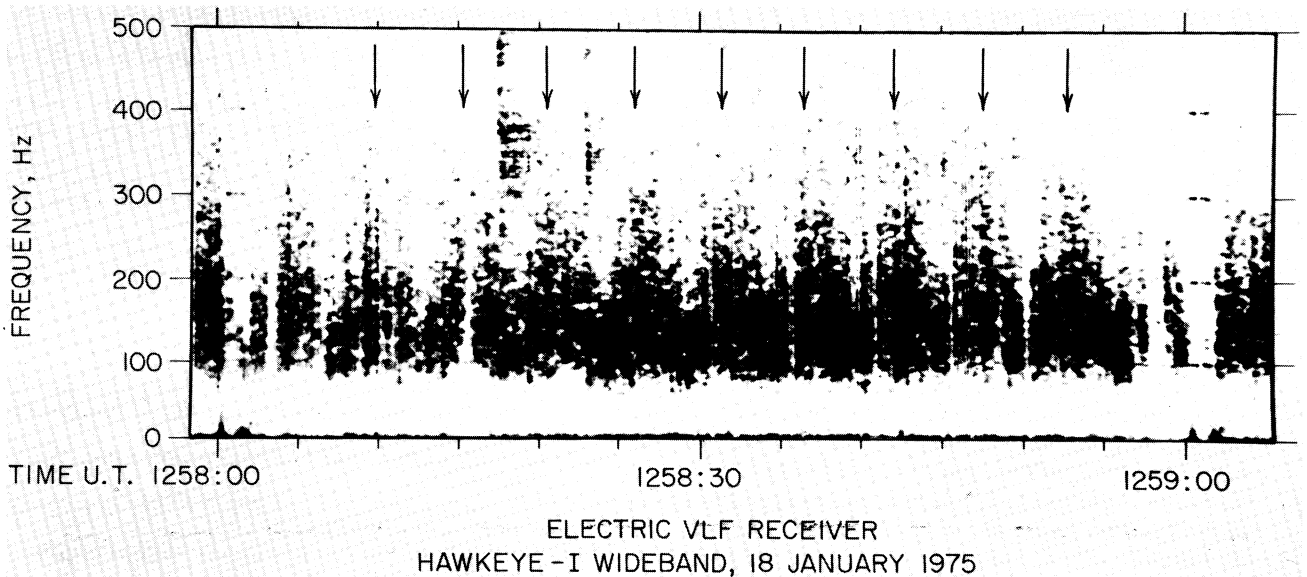


Fig. 5. Electric wide band spectrogram. Arrows correspond to times that the electric antenna is aligned in the plane of an L shell and is perpendicular to the plasmopause density gradient. The electric antenna is within 10° of being perpendicular to the magnetic field during the entire spin period.

exhibit a peak or a change in slope near 30 Hz, which it apparently does. Hence the drift wave instability is capable of producing the observed spectrum between 3 and 30 Hz.

The wide band receiver indicates that there is noise at a frequency as high as 300 Hz, although the filters indicate that the 300-Hz amplitude is 10^{-2} smaller than the amplitude at 30 Hz. If T_i is 1 eV, this implies that drift wave noise exists where $k_y \rho_i \gg 1$, and the corresponding growth rates, although positive, are small. In this regime the noise may be a product of drift waves interacting with ion cyclotron motion. This process is referred to as the ion cyclotron drift instability, and it has been observed to be unstable for values of $k_y \rho_i$ at least as large as 20 when $k_y v_d \gtrsim \Omega_{ci}$ [Hendel and Yamada, 1974].

Thus far the electrostatic waves presented here have been solely examined in the context of being produced by a density gradient. A temperature gradient between the cool (1 eV) plasmasphere and the warm (1 keV) magnetosphere will also make a contribution. If $T_e = T_i$, the temperature gradient contributes to instability for the condition $dT_e/dn_e < 0$ [Mikhailovskii, 1967]. Hence for the plasmopause where the density and temperature gradients are opposite, the growth rates are enhanced, and some turbulence may occur where the density gradients, by themselves, appear insufficient.

In addition to the drift wave instability, velocity shear instabilities have been suggested as a mechanism for producing turbulence at the plasmopause [Taylor *et al.*, 1970]. If the signal reported here has a velocity shear origin, it should exhibit a pronounced dawn-dusk asymmetry from the effect of the corotation velocity flowing against convection in the evening and with convection in the morning. On the other hand, the drift wave instability should be apparent equally at all local times.

To test for a dawn-dusk asymmetry, 10 months of data were scanned for electrostatic noise events associated with the plasmopause. From the search, 39 electrostatic noise events were identified, of which 24 were located in the 0000–1200 hour MLT sector and 15 were located in the 1200–2400 hour MLT sector. Because the satellite makes two high-altitude passes through the plasmopause each orbit, all 12-hour loca

time segments are equally sampled. The difference in electrostatic noise events located in each sector is most likely not significant. However, if the difference is significant, the asymmetry is opposite to that anticipated from a velocity shear hypothesis.

Another test for distinguishing between the drift wave instability and the velocity shear instability may be constructed by examining the response of the electrostatic noise to convection or, somewhat more indirectly, to Kp . Velocity shear noise should exist only during periods of high Kp . However, the density gradient created by fast convection will be maintained for some time after the original erosion, and drift waves should then be present not only during periods of high Kp but also during periods of low Kp following periods of high Kp . Kp for the second example presented here on February 19, 1975, is 1, while the preceding 3-hour period is 3–. The event on February 19, 1975, then is more likely to be of a drift wave origin.

SUMMARY

Hawkeye 1 crosses the high-altitude plasmopause twice each orbit. Within the plasmopause the plasma wave experiment frequently responds to electric field noise between 1.7 and 176 Hz. This noise is almost certainly electrostatic, since no comparable magnetic noise is detected. The noise is found at all local times and shows no pronounced preference for a particular local time. The noise is observed on roughly one of every five orbits and occurs only when the scale length of the plasmopause density gradient is $0.1 R_E$ or less. The close association of the noise with the region of largest plasma density gradient at the plasmopause allows it to be identified, at least tentatively, with drift waves. From this hypothesis, two tests are developed to establish the identity of the noise, the determination of the phase velocity and the determination of the wave polarization.

The spectral shape of the noise indicates a plateau between 5.6 and 56 Hz followed by a rapidly falling spectrum above 56 Hz. If the spacecraft velocity is much greater than the wave phase velocity, the effect of finite antenna length is to produce a spectral knee near 84 Hz, while the effect of finite Larmor

radius is to produce a spectral peak near 30 Hz. The phase velocities of both the Alfvén wave and the ion acoustic wave are faster than the spacecraft velocity, and hence they are unable to produce a spectral knee near 56 Hz. The drift wave, though, is sufficiently slow to produce the observed spectral shape.

The electric vector associated with the drift wave is anticipated to be primarily oriented perpendicular to both the magnetic field and the density gradient. Polarization with respect to the magnetic field could not be examined unambiguously by Hawkeye 1. However, for one case the polarization with respect to the density gradient could be examined without confusing the results with polarization with respect to the magnetic field. This case indicated that the electric field is not only polarized perpendicular to the density gradient but also that the degree of polarization is dependent upon wavelength, as has been predicted by Krall and Rosenbluth [1963].

Estimates of the growth rate and the spectrum of drift waves indicate that the drift wave instability can produce the observed electric noise and that plasmopause scale lengths of 0.1 R_E or less are sufficient to excite the drift wave instability. Further, the agreement of the spectral shape with the slow phase velocity hypothesis, the polarization of the electric field vector, the location of noise in the sharpest density gradients of the plasmopause, and the observed frequency range are all consistent with the noise being drift waves.

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