ELECTRON PLASMA OSCILLATIONS IN THE NEAR-EARTH SOLAR WIND: PRELIMINARY OBSERVATIONS AND INTERPRETATIONS

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ABSTRACT

We report here some preliminary results and conclusions of a study of electric field oscillations in the upstream solar wind. The OGO-5 orbits discussed are on the dusk (three) and on the dawn (one) sides of the earth-sun line. It is concluded that there are electron streams with $E \gtrsim 700$–800 eV produced at or near the bow shock. These streams penetrate the incoming solar wind plasma at least out to $23\,R_E$, and generate quasi-electromagnetic waves at $\omega \sim \omega_{pe}$ and $|\mathbf{k}| \gtrsim \omega_{pe}/v_B)$ where v_B is the streaming speed of the suprathermal electrons. The streams (as inferred from the wave levels) occur without regard to dawn-dusk location, as opposed to the low-frequency MHD upstream disturbances driven by backstreaming protons, which show a definitely strong preference for the dawn-noon sector. The presence of the suprathermal electron streams and associated wave turbulence indicates that some near-earth electron distributions are probably not representative of true solar wind distributions far away from the earth.

INTRODUCTION

Electric field fluctuations at or near the local electron plasma frequency have been observed regularly by the plasma wave detector experiment (PWDE) aboard OGO-5 in regions upstream from the bow shock; details of the PWDE instrumentation are given by *Crook et al.* [1969]. The sources of these oscillations at or near ω_{pe} are suprathermal electron beams in the upstream region, as described experimentally in a recent paper by *Scarf et al.* [1971] and interpreted theoretically in a paper by *Fredricks et al.* [1971*a*].

Scarf et al. [1971] showed the time correlations of the appearance of signals in the PWDE 30-kHz electric field channel and the detection of suprathermal electrons of $E \gtrsim 700$ to 800 eV by the LEPEDEA probe, when OGO-5 was in the upstream region on March 11, 1968. Also, they showed that the local number density n_o computed from data gathered by the JPL plasma probe aboard OGO-5 was consistent with the frequency of the wave phenomena simultaneously detected by the PWDE, provided the wave frequency $\omega \sim \omega_{pe} = (4\pi n_o e^2/m)^{1/2}$.

For the most commonly encountered plasma conditions near earth, the solar wind number density ranges from 1 to 10 cm^{-3}, with occasional excursions up to perhaps 60 or 70 cm^{-3}. Thus, the local plasma frequency ($f_{pe} = \omega_{pe}/2\pi$) in the near-earth solar wind commonly is 10 to 30 kHz, with occasional excursions up to some 70 kHz ($f_{pe} \sim 9\sqrt{n_o}$ kHz). Since the OGO-5 PWDE has narrowband electric field channels at 14.5, 30, and 70 kHz, along with a broadband channel covering 1 to 22 kHz, and a magnetic field channel only at 70 kHz (narrowband), the most commonly generated E-field fluctuations (10 to 30 kHz) have no simultaneous B-field data; thus, it is not possible to say whether the waves generated by the streams of $E \gtrsim 700$ to 800 eV electrons are electrostatic (longitudinal), electromagnetic (transverse), or quasielectromagnetic (mixed longitudinal and transverse) modes. The bulk speed corresponding to 800 eV is $v_B \sim 5 \times 10^9$ cm-sec^{-1}. Thus $v_B/c \sim 0.06$, so that for a wave of phase speed comparable to v_B the index of refraction $|kc/\omega| \sim 16$. This index is large, but not large enough to assume that waves generated by the interaction between streaming, suprathermal electrons

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and the cooler (10–20 eV) solar wind plasma will be purely longitudinal.

With this latter fact in mind, *Fredricks et al.* [1971*a*] have shown that quasielectromagnetic waves should be generated by 700–800 eV electron streams even if the random energy (or beam temperature) is also 700–800 eV. Quasitransverse modes of initial growth rate $\gamma/\omega_{pe} \sim 5\times10^{-4}$ and frequency $\omega/\omega_{pe} \sim 0.9996$ can be generated by beams as tenuous as $n_B/n_o \sim 10^{-3}$. The waves couple to the beam such that $\mathbf{k}\cdot\mathbf{v}_B/\omega_{pe} \sim 1.45$. If $k_{\|}$ and $k_{\perp}$ are the components of $\mathbf{k}$ along and across the beam direction ($\mathbf{v}_B/v_B$), then for $k_{\perp}/k_{\|} < 10^{-1}$, the solutions of *Fredricks et al.* [1971*a*] yield quasitransverse modes with a measurably large B component. Wherever the solar wind density n_o has been high enough to allow beams to excite 70 kHz fluctuations, both E and B components have been observed [*Scarf et al.*, 1970*a*].

The theory of the generation of the upstream plasma oscillations is discussed by *Fredricks et al.* [1971*a*]. *Fredricks et al.* [1971*b*] also have given an extensive statistical survey of the distributions in space and time of the upstream oscillations. Here we present briefly some preliminary results extracted from a study based on 31 orbits of OGO-5 as a means of illustrating a very important point: namely, that near the earth the solar wind is clearly disturbed by backstreaming electrons over the entire sunlit hemisphere as mapped by OGO-5.

EXPERIMENTAL RESULTS

A study of electric field fluctuations has been made for orbits 106 to 151 of OGO-5. This covers the time period December 2, 1968, to early April 1969, and local times (at apogee) from about 1600 to about 0800 hr. The maximum, minimum, average, and standard deviation of all electric and magnetic field channels of the PWDE were obtained for each 3.23-min (193.536-sec) experiment cycle [*Crook et al.*, 1969]. We present here a few

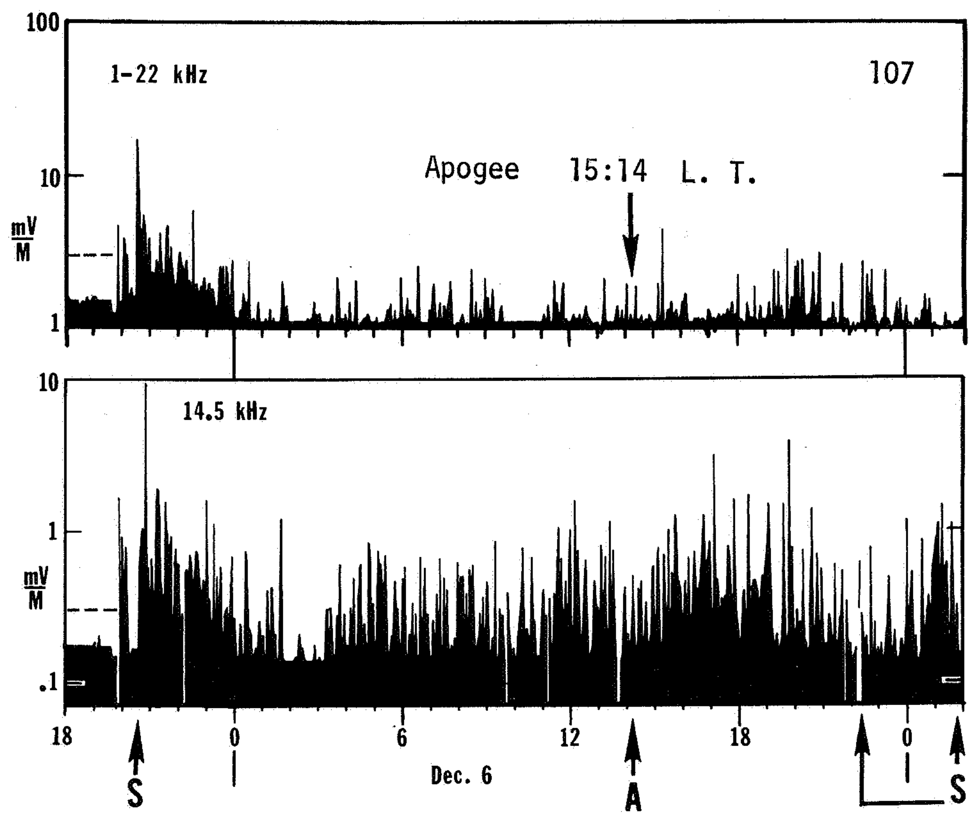

Figure 1. *Upstream electric field fluctuating levels measured on orbit 107 of OGO-5. The bow shocks and apogee are indicated by S and A, respectively. The maximum value of the electric field in the 1-22 kHz broadband each 3.23 min is plotted in the top panel, while the maximum and minimum values (bottom of panel) are plotted for the 14.5 ± 1.1 kHz narrowband channel in the lower panel. More details are given in the text. Abscissa is universal time.*

illustrative data plots extracted from this more extensive study.

The three channels most frequently active in the upstream region, from the last outbound to the first inbound encounters with the bow shock, are the 14.5 ± 1.1-kHz and 30 ± 2.25-kHz narrowband electric field channels, and the 1- to 22-kHz broadband electric field channel. As noted previously, those channels cover the expected range of the normal solar wind plasma frequency.

Figure 1 shows the 1- to 22-kHz broadband and the 14.5-kHz electric field channels for the portion of orbit 107 beyond the bow shocks. Encounters with the last outbound and first inbound bow shock are marked by an S at the two extremes of the plot, while apogee is denoted by A. This particular orbit, with apogee at 1514 hr local time, was entirely on the dusk side of the earth-sun line. The 30-kHz channel remained inactive throughout, while the 14.5-kHz narrowband and the 1- to 22-kHz broadband channels contained activity over practically the entire interplanetary portion. The 1- to 22-kHz plot shows only the maximum value each 3.23 min, while the 14.5-kHz data are maximum and minimum (~0.07 mV/M) values each 3.23 min. As discussed by *Scarf et al.* [1971], the field values in figures 1 through 4 assume a signal at the center frequency of the narrowband filters, and they are therefore lower limits, since signals at frequencies away from the center frequency suffer attenuation.

A relatively inactive orbit is described in figure 2. Here the 14.5- and 30-kHz narrowband maximum-minimum (max-min) data are plotted for orbit 109. The broadband 1- to 22-kHz channel remained at or very near threshold during the interval covered by figure 2. Although comparison of figure 2 with figures 1 and 3 (below) shows the relative quietness of orbit 109, there is sporadic wave activity throughout, indicating the presence of at least occasional suprathermal electron streams.

Figure 3 shows the 1- to 22-kHz broadband and 30-kHz narrowband channels for portions of orbit 110 while OGO-5 was in the interplanetary regime. Again, shocks are marked by S, and apogee at 1451 hr local time by A. Negligible activity was present in the 14.5-kHz E-field channel on this orbit. The simultaneous response of the 1- to 22-kHz broadband channel indicates that the true local wave frequency was probably between 22 and 30 kHz, or in the rolloff region of both filter characteristics, and far enough above

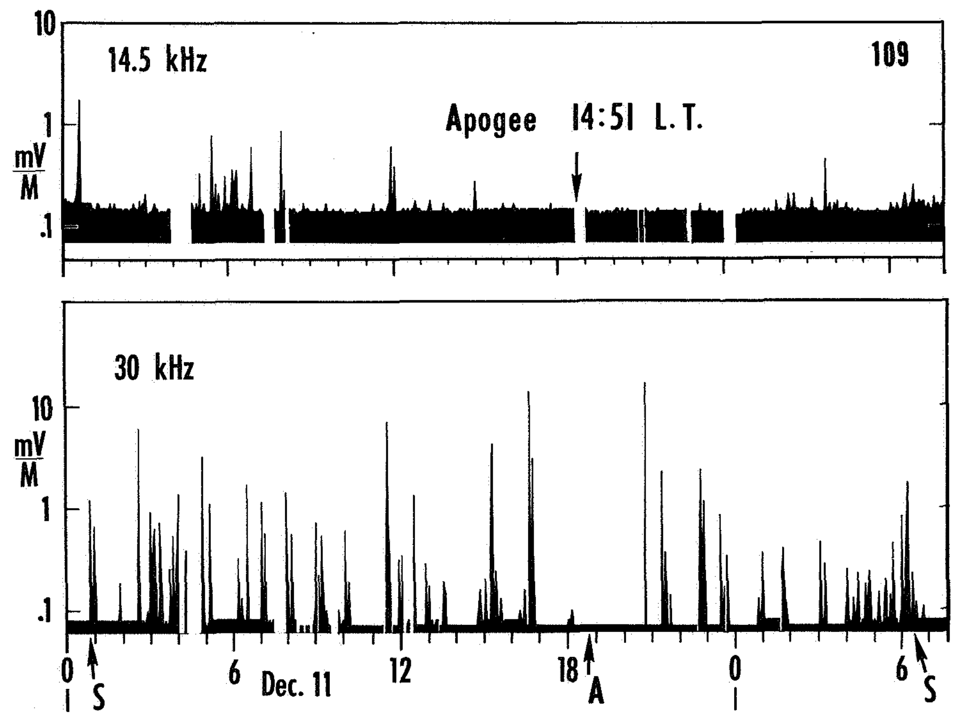

Figure 2. *Upstream electric field fluctuation (max-min) levels measured each 3.23 min on orbit 109 of OGO-5 in 14.5 ± 1.1 kHz and 30 ± 2.25 kHz narrowband channels. Broadband channel was near or at threshold for this orbit. More detail in text.*

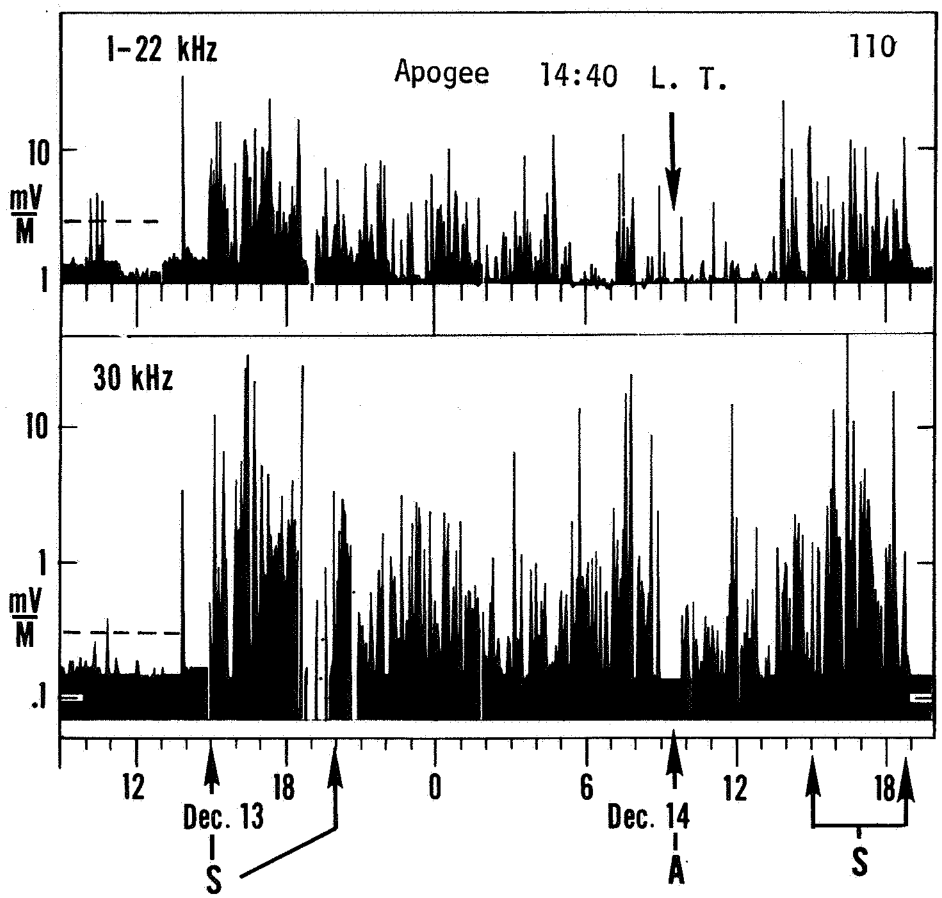

Figure 3. *Upstream electric field fluctuation levels measured on orbit 110 of OGO-5. The 1-22 kHz broadband shows only maximum value each 3.23 min, while 30 kHz narrowband plot shows max-min.*

14.5 kHz to be undetectable in that channel. These considerations imply that a very strong signal between 22 and 30 kHz was generated by electron streams interacting with a solar wind of density on the order of 6 to 10 cm^{-3}, while for orbit 107 (fig. 1) the solar wind density was on the order of 2 to 3 cm^{-3}.

Figure 4 shows the 1- to 22-kHz broadband and the 14.5- and 30-kHz narrowband max-min plots for orbit 145 of OGO-5, with apogee at 0826 hr local time. Thus, this orbit was on the dawn side of the earth-sun line. It is noteworthy that all three channels in figure 4 show significant levels of wave activity. Again, a great deal of wave turbulence near ω_{pe} occurred, while some of the broadband activity was caused by waves exciting the 3- and 7.35-kHz narrowband channels (not shown). These latter waves are associated with backstreaming protons [*Scarf et al.*, 1970*b*] and also with MHD disturbances seen by the dc magnetometers. Such proton-related electrostatic waves are rarely observed on orbits lying duskward of the earth-sun line, which is consistent with observations of *Fairfield* [1969], *Russell et al.* [1971], and others that upstream MHD waves are found with large statistical predominance in the dawn-to-noon local time sector.

DISCUSSION

Based on studies of electric field fluctuations measured by the PWDE aboard OGO-5, and by an extrapolation of the previously reported direct correlations of LEPEDEA and low energy plasma probe data with those of PWDE, it is apparent that very significant wave-particle interactions are present in the near-earth solar wind. This region therefore must be considered as disturbed upstream by the presence of the earth and its magnetosphere.

Some important aspects of these observations are summarized as follows:

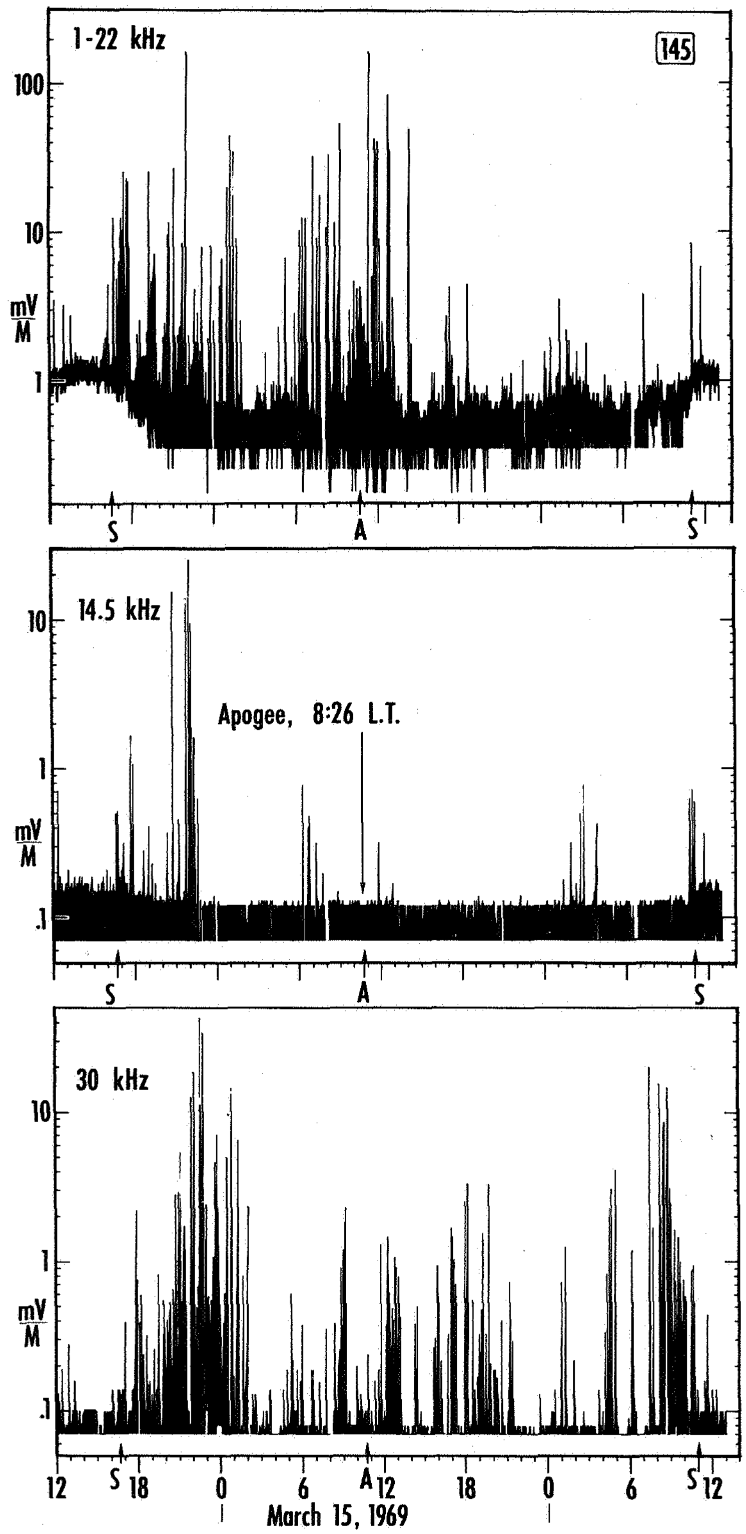

Figure 4. *Upstream electric field fluctuation max-min levels on orbit 145 of OGO-5. Details in text.*

1. Suprathermal electron streams appear to be generated by the solar wind-earth interaction, either at the bow shock or near it.
2. These streams penetrate the solar wind on both dusk and dawn sides of the earth-sun line, where they produce a significant level of wave turbulence at or close to the local electron plasma frequency.
3. The fluctuation level, or energy density in the waves, $\langle E^2 \rangle / 8\pi$, is several orders of magnitude above the solar wind thermal level ($\sim 1\ \mu V/M$), but less than the total available directed energy density in the streams. Equipartition with $\langle E^2 \rangle / 8\pi \sim n_B m v_B^2 / 2$ implies E $\sim 200\ mV/M$ wherever both wave and particle data have been available to estimate these quantities.
4. The waves are most probably quasi-electromagnetic modes driven by the electron streams, and the resulting wave turbulence levels are locally important to any heat flow or energy balance considerations.
5. Strong waves are observed even at apogee ($\sim 23\ R_E$), and *no* orbit has been found to be completely devoid of such disturbances at or near ω_{pe}, although some are more quiet than others.
6. When these waves are present it is unlikely that measurements of electron energy spectra in near-earth orbits are trustworthy replicas of deep-space solar wind electron distributions, because of the wave-particle effects described here.

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DISCUSSION

K. Schindler In connection with these large anisotropies of electrons in front of the bow shock discussed by Fredricks, it may be of interest that one can excite whistlers, by sufficiently large electron anisotropy, if they go obliquely to the magnetic field. The existence of such a nonresonant instability has recently been established in studies by myself and others.

F. Perkins I have several questions. The first question is for Bob Fredricks. Is the energy in these plasma waves sufficient to cause the electron heating that is felt to be important in front of shocks?

R. W. Fredricks No, I don't think so. These waves have high phase speeds corresponding to electrons in the part of the tail that is quite far away from the main body of the solar wind distribution and therefore these waves do not do much heating. However, if these effects last long enough the integrated result could be some nonresonant scattering.

F. Perkins Perhaps the coupling could come if the waves propagate in an inhomogeneous plasma, and consequently change their wavelength and the location of the resonance in velocity space. At any rate, I would like to mention that there is some evidence that the heat conduction instability occurs because of anisotropy of the ion velocity distribution. The heat conduction instabilities all give diffusion on the backward part of the ion velocity distribution. The backward part seems to be much colder than the forward part and one can argue that this is circumstantial evidence for the occurrence of the heat conduction instability.

Last, I would like to ask Dave Forslund whether the electromagnetic ion cyclotron instability, that seems to be so easily set off, has a significant component of plasma density fluctuations with it so that it might be relevant to the radio star scintillations.

D. W. Forslund It may have some density fluctuation. I haven't checked it in detail, but our computations show that there is a significant electric field in the direction of **k**. In fact, it can be larger than the component perpendicular to **k** even though the electromagnetic part is polarized as required for an electromagnetic wave. I suspect that the large **E** field in the direction of **k** should cause some density fluctuations.

M. Montgomery I have a couple of questions for Bob Fredricks. First, your figures indicate that the plasma frequency noise was present most of the time. Are you implying, then, that the electron streams in the bow shock are observed most of the time? Is there a direct and consistent correlation between the noise and the upstreaming electrons?

R. W. Fredricks There is insofar as we have been able to determine from simultaneous LEPEDEA measurements. Whenever the waves are seen there are bursts of these electron fluxes above 380 V with this characteristic. But this correlation study is limited to early March 1968 data when Frank's instrument was on. Unfortunately, there was a failure in his instrument on March 12, 1968. Therefore, I am extrapolating because during the interval covered by the simultaneous measurements the waves were always associated with the disturbed electron distribution.

M. Montgomery Do you mean correlated with the upstreaming electrons? Can we assume then from your data that most of the time when OGO-5 is outside the bow shock there were upstreaming electrons present?

R. W. Fredricks There are many bursts of electrons, but there can be time intervals of minutes when none occurs. One point that I didn't mention is that when we see these high-frequency electron plasma frequency waves there are no correlations with magnetic perturbations of any size.

M. Montgomery That brings to mind the next question I was going to ask. That is, when you see these noise bursts, what is the field configuration? Is the field configuration consistent with OGO-5 being on a line of force connected with the bow shock?

R. W. Fredricks I haven't done a systematic study yet, I can't answer that question. But there seems to be no systematic difference between the dawn and dusk quadrants. This is not true of the proton generated noise, which seems to be concentrated on the dawn side of the earth sun line.

M. Montgomery And then the last question is, from the LEPEDEA measurements can you estimate the amount of energy flux being carried away from the shock?

R. W. Fredricks I haven't calculated it yet. I don't know.

M. Montgomery That is a relatively important quantity to know.

R. W. Fredricks This does indicate when this is going on the local heat flux vector could be pointing in some arbitrary direction. It doesn't have to be from the sun or back towards the sun.

M. Montgomery It worries me a little bit that you see it so much of the time, especially when the magnetic field line upon which OGO-5 is located is not likely to be connected to the bow shock.

R. W. Fredricks Well, I believe I have an answer for that, but right now I don't want to commit myself to a statement that there is *no* field alinement correlation. This requires a further study.