Nearly monochromatic waves in the distant tail of the Earth

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[1] The Waves experiment on the Wind satellite has been used to survey the occurrence of nearly monochromatic waves in the Earth's tail region. Several hundred examples of monochromatic waves were observed during excursions into the tail, including 218 examples during a 4-day passage of the Wind satellite through the geotail at -90 R_E. We present an investigation of the characteristics of these waves and of the environment in which they are found. The waves are electrostatic, and the distribution of the angle E to B shows peaks at 0° and 90°. The waves near 90° sometimes show electron cyclotron harmonics, but these are very rare in the waves near 0°. It seems that the waves occur most commonly in or near the plasma sheet boundary layer, and it is probable that they are convected downstream from reconnecting regions. *INDEX TERMS:* 2772 Magnetospheric Physics: Plasma waves and instabilities; 2748 Magnetospheric Physics: Magnetotail boundary layers; 2764 Magnetospheric Physics: Plasma sheet; 2744 Magnetospheric Physics: Magnetotail; *KEYWORDS:* magnetotail, reconnection, waves

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1. Introduction

[2] Nearly monochromatic waves in the geotail were first reported by *Kojima et al.* [1997], who showed that some were consistent with Langmuir waves but others were electron cyclotron harmonics. *Farrell et al.* [2002] found a close association with the diffusion region of a reconnection event in one case, a case reported by *Oieroset et al.* [2001]. The wave was quite intense, 50 mV/m, and Farrell et al. suggested a connection with wave-mediated diffusion.

[3] The Wind satellite, though its main purpose is to monitor the solar wind upstream from the Earth, has made several excursions into the Earth's tail region. Its experiment complement for observations of waves is exceptionally complete (Waves [*Bougeret et al.*, 1995], and so a survey was made of nearly monochromatic waves during most of the tail excursions. Several hundred examples of monochromatic waves were observed during these excursions into the tail, including 218 examples during a 4-day passage of the Wind satellite through the geotail at -90 R_E. This larger number indicates that such waves are not only found in the reconnecting region, so it becomes interesting to establish their origin and behavior. We present an investigation of the characteristics of these waves and of the environment in which they are found.

[4] Many characteristics of these waves, especially those propagating nearly perpendicular to the magnetic field, are similar to those found by *Shaw and Gurnett* [1975] in their pioneering study with their experiment on IMP 6, However, that study was confined by the orbit of IMP 6 to distances less than 30 R_E.

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2. Investigation Method

[5] A selected example of the nearly monochromatic waves is shown in Figure 1. These data are obtained from the Time Domain Sampler (TDS) part of the Waves experiment. The TDS makes rapid digital samples of the waveforms of the electric field on two of the Waves antennas, X and Y, which are in the spin plane which is also the plane of the ecliptic. The sample rate varies from a maximum of 120,000 samples per second to rates slower by successive factors of 4. An event is a series of 2048 samples. A "smart" system on board selects the best events for telemetry to ground. During the period under discussion, the selection criterion was simply the event having the largest single sample. Another channel selects randomly chosen events for telemetry, in order to provide synoptic data. The data are Fourier analyzed on the ground. Note that the waveform of Figure 1 is modulated, and hence is not truly monochromatic. In fact, the spectrum shows a small peak, separated by 118 Hz on the low-frequency side of the main peak, which is about 25 dB lower than the main peak.

[6] Our survey was made by computer, which first found the peak frequency in the spectrum and then determined its bandwidth. Events were selected which met the criterion that (1) the bandwidth was less than 0.05 of the peak frequency or twice the FFT frequency resolution, whichever was larger, and (2) the frequency was close to the plasma frequency as determined by the Wind plasma instrument

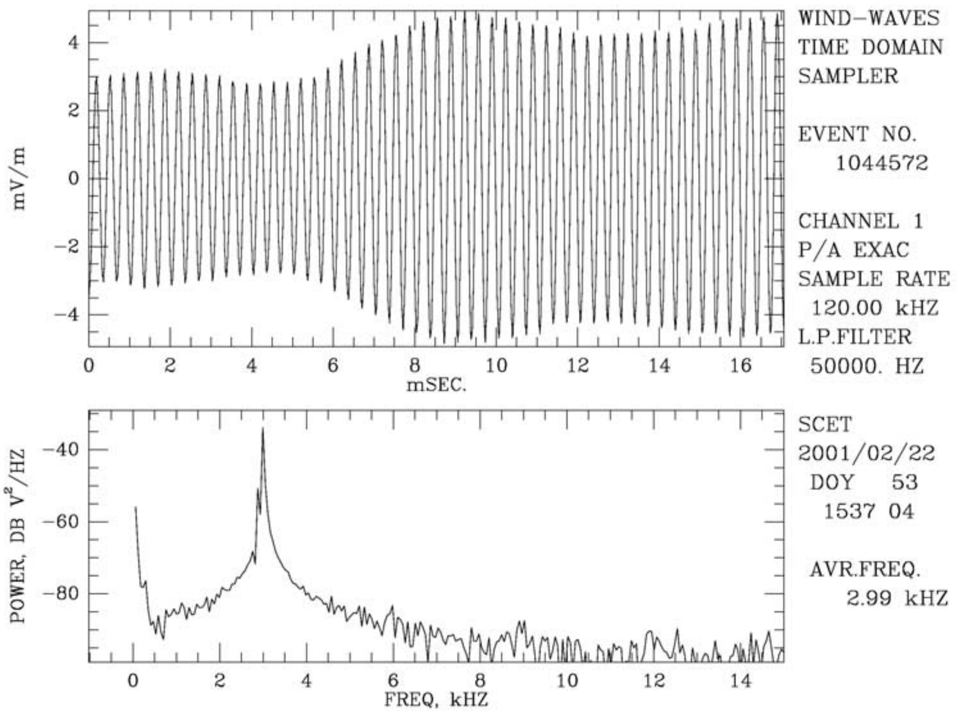

Figure 1. An example of a nearly monochromatic wave as captured by the TDS in the geotail.

3DP [*Lin et al.*, 1995]. Bandwidths were calculated as the variance of the frequency weighted by the spectral power. At the highest sample rate the fundamental frequency of the analysis, and therefore the frequency resolution, is 59 Hz so that bandwidths narrower than this cannot be determined. Our bandwidth calculation gave 30 Hz for the bandwidth of Figure 1, but for the highest sampling rate, calculated bandwidths smaller than 59 Hz depend on just where the true peak frequency falls in relation to the Fourier frequencies and this difference is not significant. The frequency resolution is better at lower sampling rates, and it seems that most of the events have a natural bandwidth of the order of 50 Hz due to the burstiness inherent in waves generated by an instability.

[7] Note that the narrow-band procedure does not completely preclude the presence of smaller peaks separated from the main peak in the selected event, and hence does not preclude the presence of electron cyclotron harmonic waves as part of the spectrum, as found by *Kojima et al.* [1997]. The procedure does, however, militate against selection of spectra with peaks close together. A visual inspection of spectra and their waveforms was made for a small subset. The visual inspection did show that there were some spurious events (the ones found were removed), and that a certain fraction, several percent, was missed, mostly due to partial data transmission. However, the survey results should convey a reasonably accurate account of the occurrence of the monochromatic waves.

[8] The period searched extended from 12 December 1999 to 13 September 2001 with some omissions when Wind made only short excursions into the tail or when the operational mode of the TDS was not suitable for this study. In Figure 2 are shown the results of this computer search. The lines show the trajectories of Wind which were

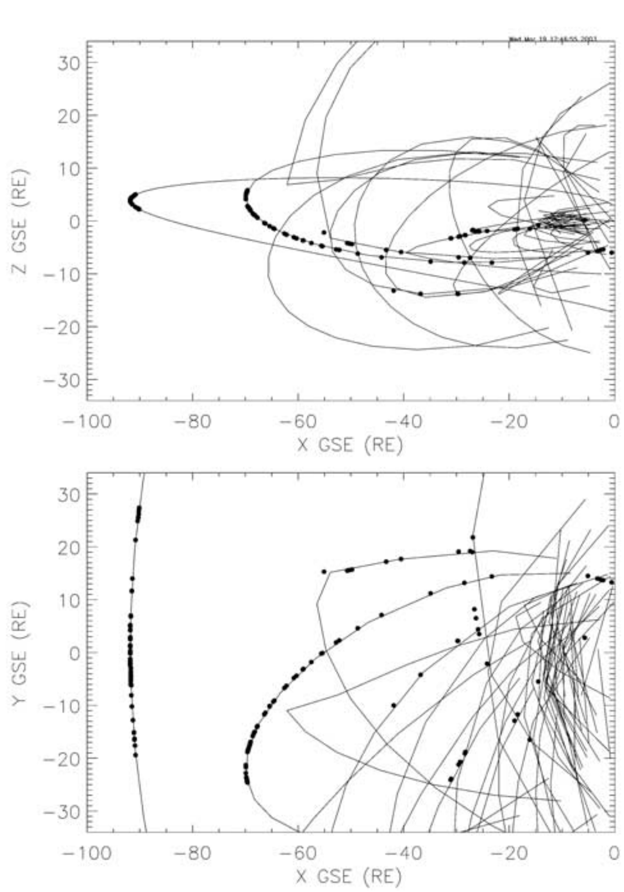

Figure 2. Points where nearly monochromatic waves were observed, together with the orbits of Wind in the tail region.

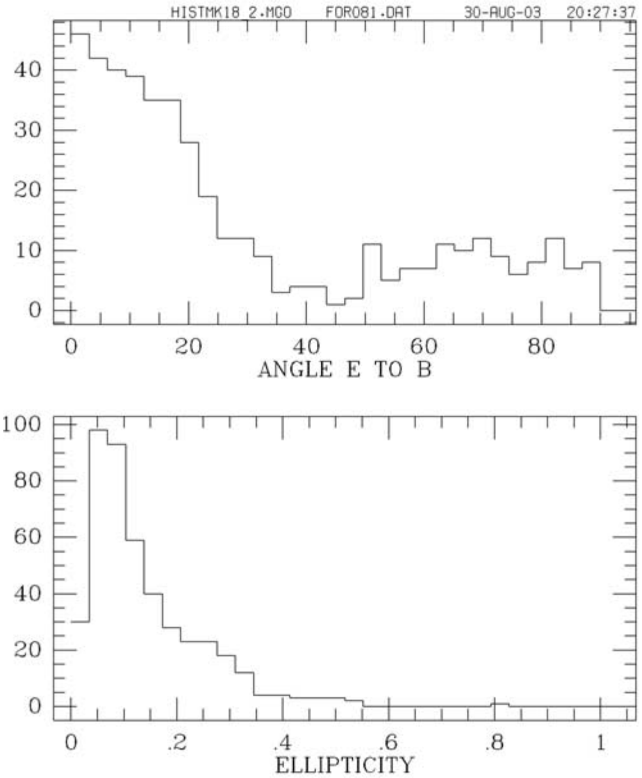

Figure 3. Histograms (top) of the angle between the average electric field and the magnetic field and (bottom) of the (two dimensional) ellipticity of the waves.

surveyed, and the dots show the 443 observations of nearly monochromatic waves which met our criteria. It will appear that there are many fewer than 443 dots, because the events occur in bunches and the dots overlap.

3. Characteristics

[9] For each event, the variance matrix (two-dimensional as only two components of E are measured) was calculated and its eigenvalues and eigenvectors found. The direction of the eigenvector with the largest eigenvalue was taken as the principal direction of the projected electric field, E, and the ratio of the smaller eigenvalue to the larger was taken as a measure of the ellipticity of the waves. In Figure 3 are shown histograms of the angle between E and the magnetic field B and of the ellipticity. It is clear that the waves generally have small ellipticity, and that their polarization falls into two classes, one class primarily parallel to B and another primarily perpendicular to B. At the plasma frequency and below, as here, linearly polarized waves are primarily electrostatic. Note that what is shown is the projection of the vectors B and E on the ecliptic plane. Parallel vectors remain parallel in projection, but perpendicular vectors do not. The peak at about 70° in the projection is probably due to vectors which are actually perpendicular. It is natural to think that the waves parallel to B are Langmuir waves, and that the waves perpendicular are upper hybrid waves or electron cyclotron harmonic waves (ECH, sometimes called n + 1/2 waves, and usually identified with Bernstein modes) as found by *Kojima et al.* [1997] in the geotail and earlier by *Shaw and Gurnett* [1975] nearer the Earth. The magnetic field usually was of the order of 10 nT for an electron cyclotron frequency of 280 Hz, so that the upper hybrid frequency differs little from the plasma frequency, which was usually 2 to 5 kHz, but sometimes up to 10 kHz.

[10] The waves generally are of fairly low amplitude compared to the case analyzed by *Farrell et al.* [2002]. In Figure 4 is shown a histogram of the wave amplitudes. These have been sorted into three regions of distance down the geotail. It will be seen that the event reported by Farrell et al., 50 mV/m, is of the order of the largest of the events which our survey found. It will also be seen that events in the region closest to the Earth are weaker, as the average amplitude in decibels with respect to 1 $(mV/m)^2$ is smaller than for the other two regions. The difference between the outer two regions is not regarded as statistically significant. On the other hand, the data suggest that monochromatic waves are more frequent at the farthest regions of this survey. For the pass of Wind through the tail at -90 R_E in February 2001 (see Figure 2), 218 events were collected in 4 days, or 54 events per day. For the pass in Figure 2 which extends to -70 R_E, there were 78 detected events in 5 days, or 16 events per day. It is also apparent that there are only a few events inside -20 R_E, in spite of the numerous orbits which traverse that region.

[11] A detailed investigation, i.e., a look at the individual waveforms and spectra of a number of events during the

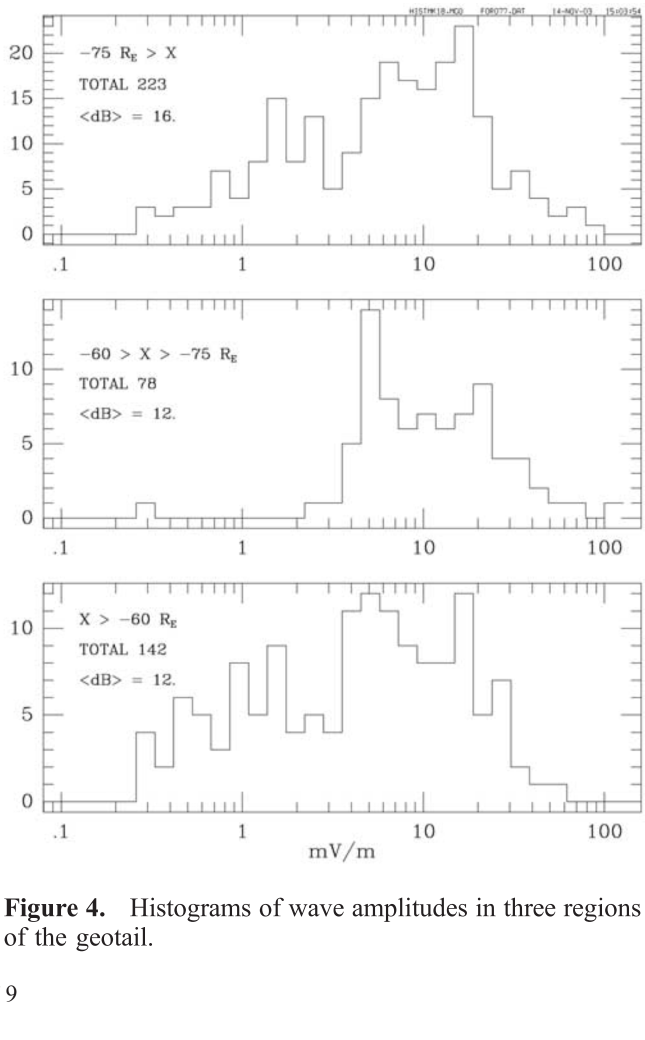

Figure 4. Histograms of wave amplitudes in three regions of the geotail.

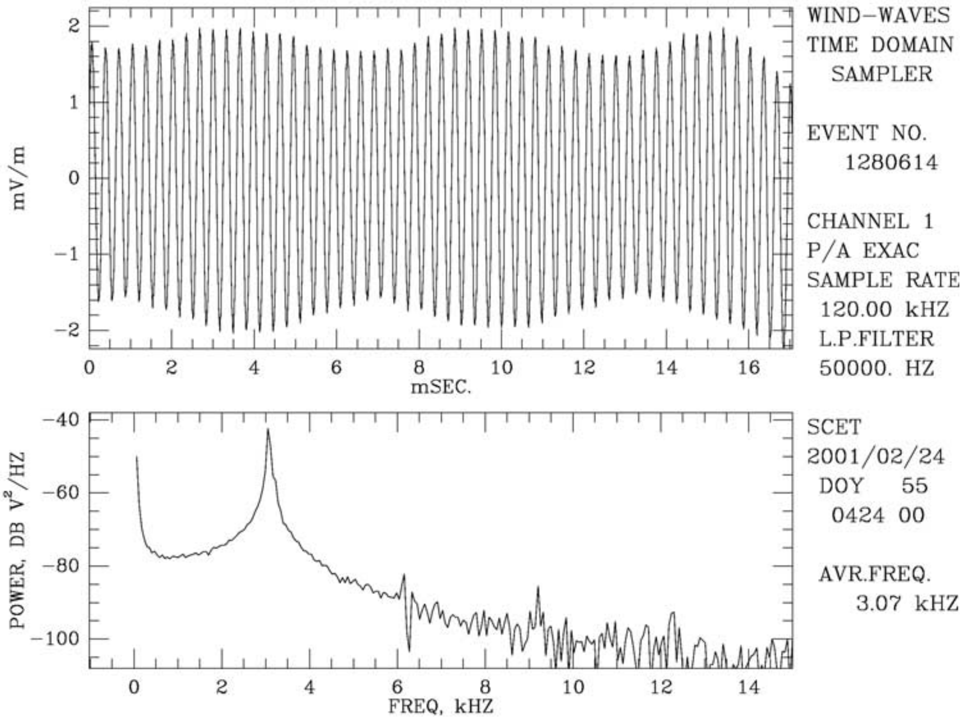

Figure 5. An example of a wave showing regular modulation near the electron cyclotron frequency but with only a single spectral peak.

-90 R_E pass of Wind through the geotail, was made. During this pass the computer search found 53 events with a projected angle E to B of greater than 40° (compare Figure 3), and all of these were plotted and analyzed. There were 165 events with projected angles of less than 40°, and a randomly selected set of 53 of these events was similarly treated. It was expected that some of the quasi-perpendicular events would be n + 1/2 waves and so would have power spectra showing multiple peaks separated by the electron cyclotron frequency. In fact, the situation was more

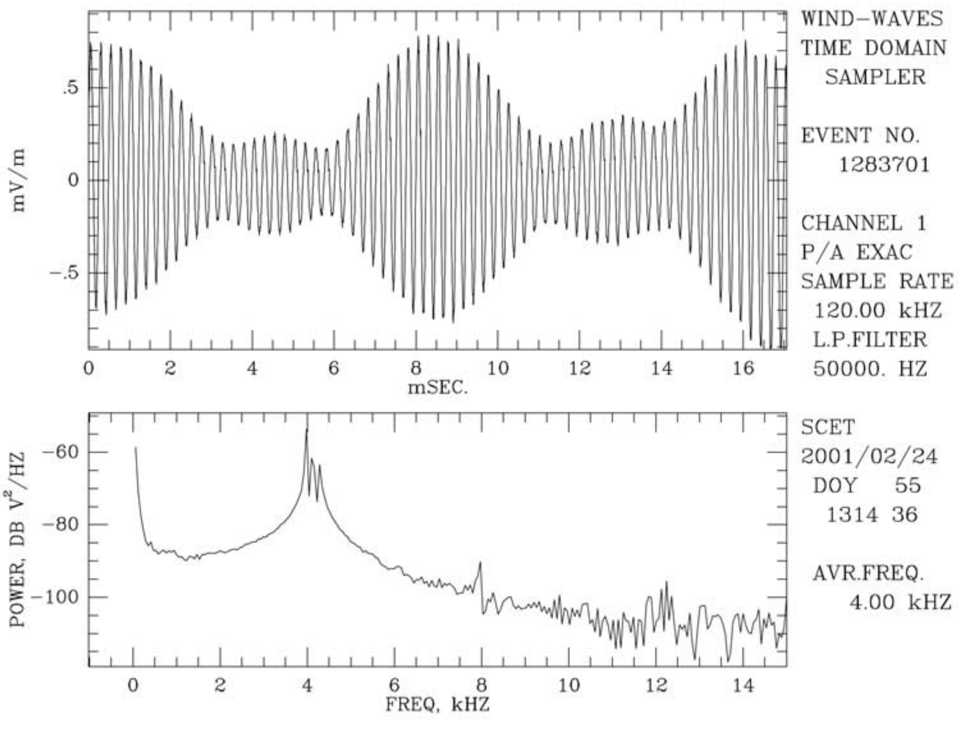

Figure 6. An example of the expected spectrum of n + 1/2 waves.

complicated, in that a number of events showed some envelope modulation at periods corresponding to frequencies separated by roughly the cyclotron frequency, but many of the modulations were not strong enough to produce peaks in the power spectrum. The example of Figure 1 is such a case for which, however, we would say that the modulation is irregular. That event followed a plasmoid by about 7 min, but the magnetic field had subsequently been stable at about 9.5 nT for a cyclotron frequency of 270 Hz. This frequency is judged sufficiently different from the actual splitting of 118 Hz that Figure 1 does not represent a mixture of n + 1/2 waves but represents merely the results of an instability which grows for a range of wavelengths and frequencies. For contrast, an event which was judged to represent two n + 1/2 waves but with only a single peak in the power spectrum is shown as Figure 5, and an event with three clear peaks is shown as Figure 6. However, it can be seen that the division of the observed waves into n + 1/2 waves or Langmuir waves is a matter of judgment, depending on whether the modulation is judged to be regular or irregular. As judged, the quasi-parallel set contained only four events which were n + 1/2-like, but one of them was as perfect as Figure 6. Of the 53 quasi-perpendicular events, 32 showed multiple peaks or modulations near the cyclotron frequency.

[12] The quasi-perpendicular waves were not randomly distributed among all waves. All of the quasi-perpendicular waves were found between 23 February, 2000 UT and 24 February, 2015 UT, for which Wind was between Y(GSE) = -3.6 to -16.5 R_E, hence on the dawn side of the tail. Quasi-parallel waves were observed from Y(GSE) = +27.3 to -5.2 R_E, roughly consistent with symmetry around an aberrated tail. The quasi-perpendicular waves at -90 R_E had an average logarithmic amplitude which was 14 dB smaller than the quasi-parallel waves, but for the whole set the quasi-perpendicular waves were only 7 dB weaker.

[13] Since ion acoustic waves have a phase speed which is independent of frequency to first order, they usually have broad spectra as the resonance condition is satisfied over a range of frequencies. The narrowband criterion therefore serves to exclude ion acoustic waves, which might otherwise have been included, as the ambient plasma frequency is not accurately determined. (Nevertheless, the computer-generated set of 53 quasi-perpendicular waves contained two ion acoustic events, and the quasi-parallel set contained seven. These were removed.) Hence the observations are consistent with waves in the Langmuir upper hybrid mode.

4. Electron Beams

[14] Langmuir waves are often generated by electron beams which form a bump-on-tail distribution. This suggests that this may be the case here. Some of the events were analyzed for electron beams. No beams, in the sense of a positive slope in the reduced distribution function, were found, but all of the events which were analyzed showed energetic electron streams. In some, but not all cases, the streams either were just beginning at the time of the Langmuir waves or represented a significant intensification of an existing beam. It is possible therefore that a bump-on-tail distribution was briefly formed by the time-of-flight mechanism. As is well known, the time resolution of plasma measurements makes the measurement of distribution functions during these rapidly changing events somewhat uncertain.

[15] It seems that the waves are primarily found in the plasma sheet boundary layer where energetic electron and ion beams are known to exist. Evidence is presented in Figure 7, which shows the first encounters with monochromatic waves on 21 February for the distant traversal of the tail region at about -90 R_E, on the +Y(GSE) side of Figure 2. The top two panels in Figure 7 show the frequency and amplitude of the monochromatic waves found by our search. The frequency panel also shows the plasma frequency computed from the density measured by the 3DP experiment. The next two panels show electron energy flux in several energy ranges, and the next shows energetic ion flux. The next panel is B_x, the sunward component of the magnetic field, and the bottom panel is the plasma density. It will be seen that the waves generally occur together with short increases in the energetic particles and decreases in B_x, which we interpret as encounters with the plasma sheet boundary layer and then with the plasma sheet itself.

5. Reconnection, or Other Sources

[16] Reconnection of the Earth's magnetic field to the field of the solar wind accelerates particles, and it is natural to consider whether the electron streams found above are from reconnection events. As we have seen, the monochromatic waves are common, while the chance of being in the active region of a reconnection event is small, so that if reconnection events are the source of the electron beams, they must be remote from the spacecraft.

[17] We are therefore led to consider whether there is a correlation between the occurrence of monochromatic waves and the auroral index AE, an indication of substorm activity and reconnection. In this, we concentrate on the most distant pass of Wind, at about -90 R_E. Also, as the coverage of the TDS is less complete at this distance, we add data from the "FFT" part of the instrument. The FFT instrument makes on-board Fast Fourier Transform analyses of sets of 1024 samples in several frequency bands. The band of most use for this study is the range from 0 to 11 kHz. These analyses are telemetered about every 2 min, and so give more complete coverage of wave activity. However, neither instrument has anywhere near full coverage, and it can be seen that sometimes events seen by one instrument are not seen by the other. It follows, of course, that many events are not captured by either instrument.

[18] At the same time, as has been shown in Figure 7, the monochromatic waves tend to occur in the plasma sheet boundary layer. We expect, therefore, that Wind must be in the right place (in the boundary layer), and also at the right time (auroral activity indicating active reconnection) in order that nearly monochromatic waves be observed.

[19] The clearest correlation of the waves with the AE index occurs early on 21 February and is seen in the data of Figure 7. The AE index was quiet, values less than 100, from about 0500 UT to the increase shown at about 0930 UT. Although Wind had crossed the magnetopause much earlier, the first monochromatic wave was observed at 0928 UT. Following that first wave, waves were observed with each of the next few brightenings of the AE index until about 1400 UT when the auroral index faded.

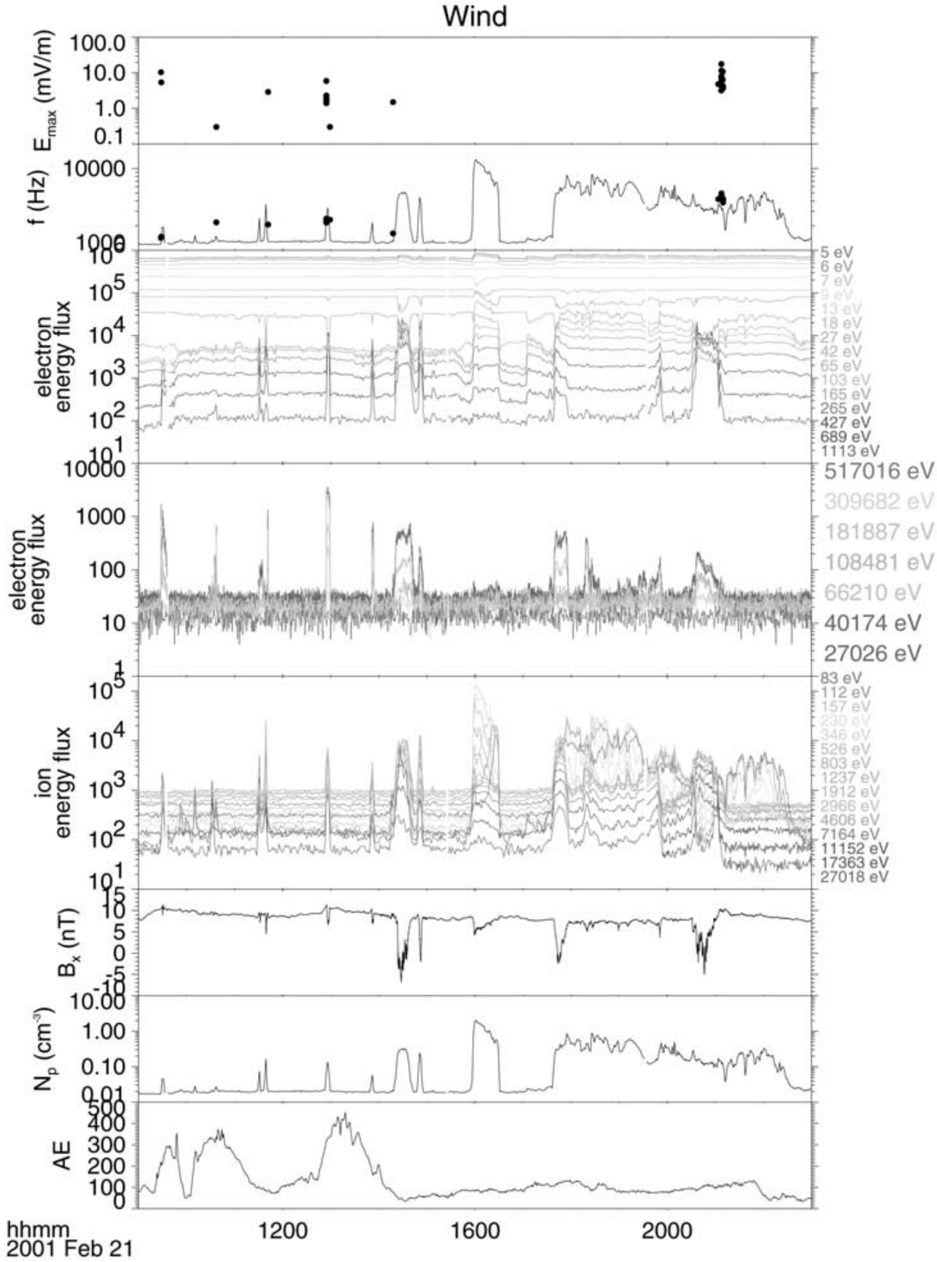

Figure 7. Monochromatic waves, associated with energetic particle flows. The dots show the frequencies and amplitudes of the waves captured by the TDS. The other data show that the waves are characteristic of the plasma sheet boundary layer, the plasma sheet itself being marked by reductions in B_x. See color version of this figure in the HTML.

[20] Later that day, at 2106 to 2110 UT, a positive correlation with the quick-look AE is lacking, as there is a sequence of monochromatic waves with no increase in AE. Hence we have also included another measurement, of Auroral Kilometric Radiation AKR, which is also known to be a good indicator of auroral activity. These data are the integrated power in the band 146–390 kHz, taken from the Rad1 part of the Wind-Waves instrument. In Figures 8 and 9 are shown dynamic spectra from the EX antenna and the FFT instrument, together with the auroral AE index and the previously discussed events from the TDS instrument. In these figures, the dots in the top two panels show the occurrence, frequency, and amplitude for the TDS events. Below that is shown the X(GSE) (sunward) component of the magnetic field, in order to show when the plasma sheet is encountered. The next panel shows the quick-look AE index from the World Data Center at Kyoto, the next panel shows the power in AKR, and the bottom panel shows a dynamic spectrum from the FFT. For the afternoon of 23 February in Figure 8 it will be seen that B_x is mainly antisunward and so Wind is south of the current sheet. At times, B_x goes through zero, and sometimes becomes about 10 nT sunward. Zeros are interpreted as immersions in the plasma sheet, and reversals mean that the satellite has

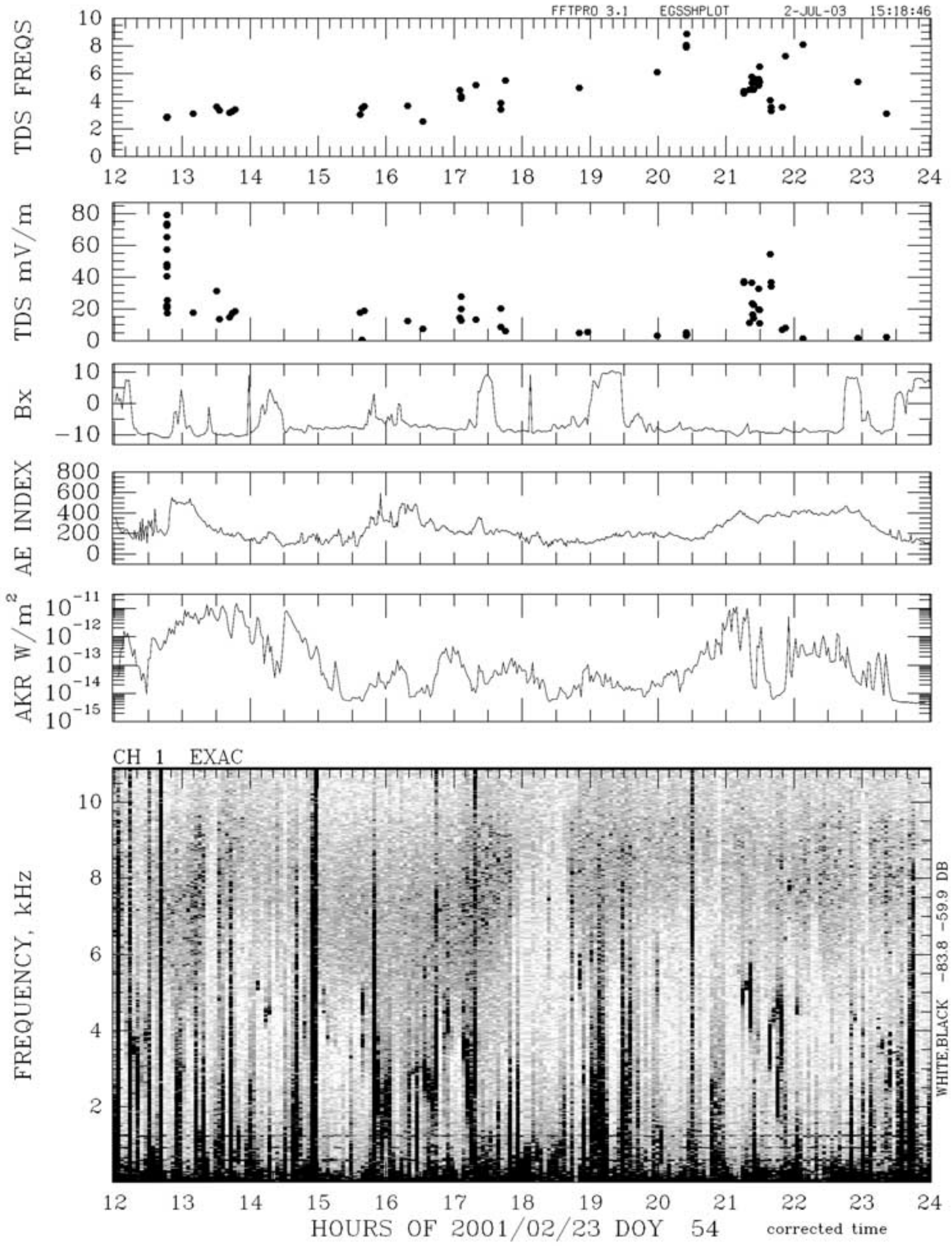

Figure 8. Wave activity as seen by the TDS and FFT instruments of Waves, together with two indicators of auroral activity, the AE index and the AKR power, for the afternoon of 23 February 2001.

passed to the north of it. At about 1300 UT, there is an increase in the AE index at a time when AKR is already strong, together with an encounter with the plasma sheet, as shown by the drop in B_x toward zero, which coincides with a series of unusually strong waves. Plasma sheet encounters at 1600 and 1730 UT are bracketed by wave events. On the other hand, there are a number of wave events near 2130 UT which are approximately simultaneous with mild increases of the AE index and strong AKR, but it is not clear where Wind is with respect to the plasma sheet. There is, however, a small change in B_x at 2120 UT, which may indicate a near approach. The FFT instrument shows falling and rising tones, which are assumed to be near the plasma frequency and so indicate a region of rapidly changing density, again consistent with a near approach to the plasma sheet. AKR is weak just after the bulk of the wave events although AE remains constant, which might indicate that AKR is being refracted away from a density increase. When the AE index drops below 200, there are few events, either in the FFT or the TDS. In this case there is an approximate, but not precise, correlation between the waves and the position of Wind in the boundary layer and indications of auroral activity. It will be shown later that the waves on the afternoon of 23 February and on 24 February seem to have a character different in various respects from the waves seen earlier.

[21] Figure 9 shows more data from the afternoon of 21 February, some of which is also shown in Figure 7. There is a series of wave events at 1300 UT which occurs at an increase in the AE index and supports the previous

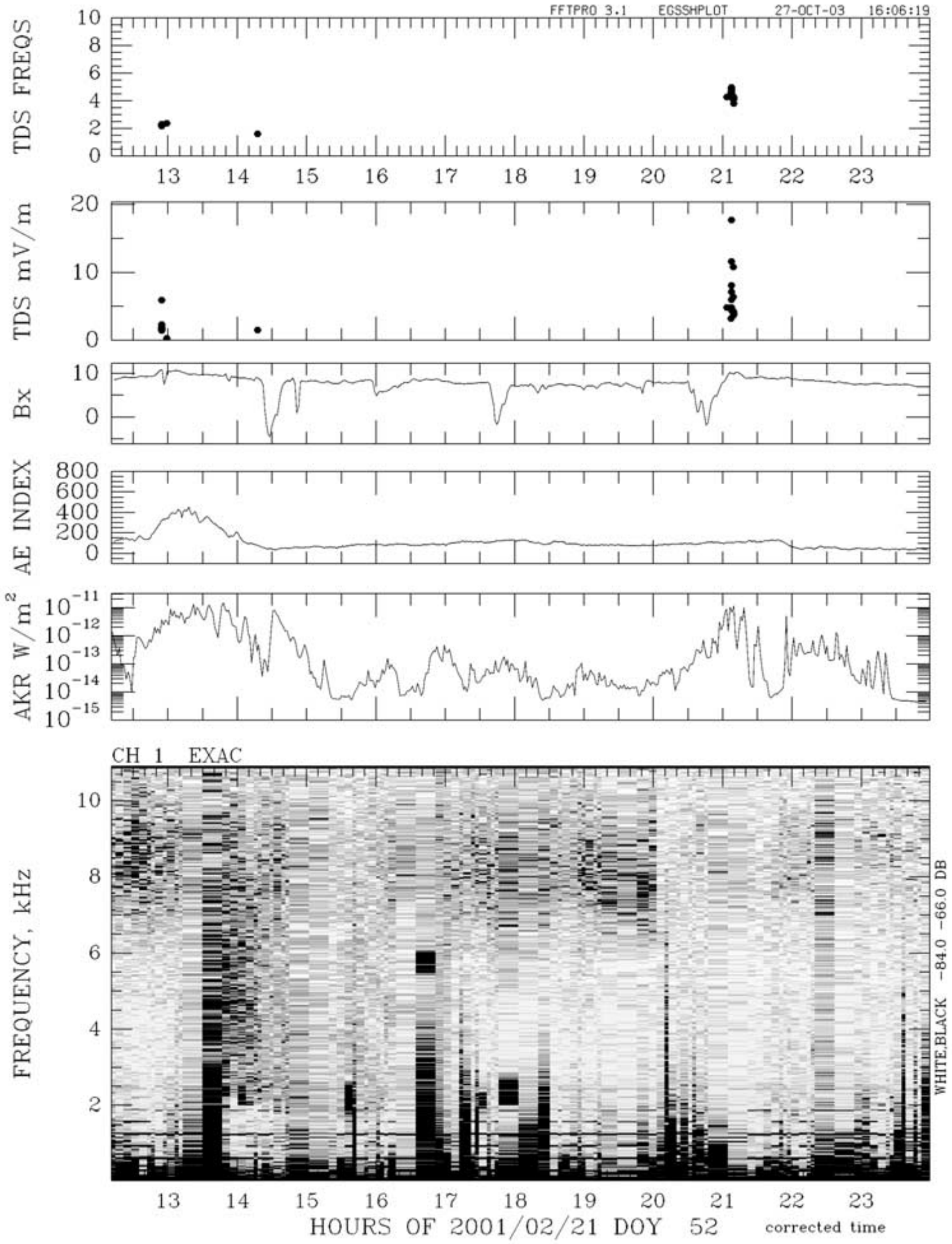

Figure 9. Same as Figure 8 for the afternoon of 21 February 2001.

correlations. The TDS events occur in a very short time period and do not show well on the FFT plot. The FFT plot shows that there is additional wave activity sporadically during the afternoon which was not captured by the TDS, but not much activity in the AE index, which remains small, of the order of 100 nT. However, then there is another period of quite intense wave activity between 2100 and 2200 UT and only a minor increase in AE, which provides a counterexample to the events just discussed. However, the power in AKR shows that auroral activity remains moderate to high. At 2100 UT, there is a modest but distinct increase in AKR. (At about 1630 the rapidly rising and slowly falling signal is a solar type III burst and is not part of the AKR.) Apparently, there was some activity which is usually interpreted as auroral activity, but any aurora must have occurred in daylight or far from a station of the AE network. It was expected that there would be correlation between the monochromatic waves and the usual indicators of substorm activity. There are some good examples, but many counter-examples. It is not clear whether the lack of correlation is due to an erroneous idea of the physics, or whether Wind was simply at the wrong place or the TDS failed to identify the desired events.

[22] Reversals of the plasma flow are usually taken as indicating nearby reconnection. There is one example of reversal in the 3DP data during the excursion at $-90\ R_E$. It occurred between about 1420 and 1440 UT on 21 February (Figure 7). There is no exceptional wave activity during this period.

[23] It may be that sources other than electron beams created by reconnection are the cause or one of the causes of the waves. The peak in the angle distribution for

perpendicular propagation suggests that a loss cone instability [*Melrose*, 1986, sect. 4.5] may be playing a role. Loss cones are obviously important in the aurora, the losses being due to the precipitating particles which cause the luminosity. The occurrence of these waves in the plasma sheet boundary layer also is suggestive of an auroral connection.

6. Conclusions

[24] An unexpectedly large number of nearly monochromatic waves has been found in the Earth's magnetotail by the Waves experiment on Wind. They are consistent with Langmuir-upper hybrid waves. The distribution of angles between the wave electric field and the ambient magnetic field showed peaks at 0° and near 90°.

[25] Our survey method was not well suited to finding electron cyclotron harmonic waves, as were found by *Kojima et al.* [1997]. However, a set of n + 1/2 waves was found by using their property of propagation nearly perpendicular to the magnetic field. They are slightly less intense than the quasi-parallel waves, and are located toward the dawn side of the geotail, whereas the quasi-parallel waves are nearly symmetrically distributed around the tail.

[26] The occurrence frequency of such waves seems to increase to the farthest region of the tail explored by Wind, $-90\ R_E$. An automated search of the Time Domain Sampler data in a 4-day period at $-90\ R_E$ found 218 events. Most of the wave events were found in the plasma sheet boundary layer.

[27] All of the wave events which were investigated for plasma distribution functions were associated with energetic electron flows, suggesting association with distant reconnection. However, there was no evidence for beams, i.e., reduced distribution functions with a positive slope. Hence the waves are probably convected from elsewhere. An attempt was made to associate these flows with reconnection events through correlation with the AE index. The data are suggestive of a broad correlation with substorm activity, and there were clear associations with increases in the AE index in most cases, and increases in AKR in some cases. However, overall, the correlations were not very strong. They were stronger for the quasi-parallel waves.

[28] The peak near 90° with the magnetic field is an indication that a Langmuir wave instability due to a loss cone might play an important role. The different spatial distribution and angular distribution for quasi-parallel and quasi-perpendicular waves suggests two different populations. It may be that two mechanisms generate these nearly monochromatic waves.

[29] **Acknowledgments.** The authors thank the World Data Center at Kyoto for use of the quick look auroral indices, the National Space Sciences Data Center and R. P. Lepping for the magnetic data, the NSSDC for some of the plasma data, and Cynthia Cattell and George K. Parks for useful discussions. The work at the University of Minnesota was supported by NASA under grant NASG-10178.

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