Narrowband Large Amplitude Whistler-mode Waves in the Solar Wind and Their Association with Electrons: STEREO Waveform Capture Observations

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Received 2020 March 16; revised 2020 May 2; accepted 2020 May 18; published 2020 July 9

Abstract

Large amplitude (up to 70 mV m⁻¹) whistler-mode waves at frequencies of ~0.2–0.4 fₑ (electron cyclotron frequency) are frequently observed in the solar wind. The waves are obliquely propagating at angles close to the resonance cone, resulting in significant electric fields parallel to the background magnetic field, enabling strong interactions with solar wind electrons. Very narrowband (sinusoidal waveforms) and less coherent waves (more irregular waveforms) occur, but do not have a bimodal distribution. Frequencies and/or propagation angles are distinctly different from whistler-mode waves usually observed in the solar wind, and amplitudes are 1–3 orders of magnitude larger. Waves occur most often in association with stream interaction regions, and are often “close-packed.” Wave occurrence as a function of normalized electron heat flux and beta is consistent with the whistler heat flux fan instability for both the narrowband coherent and the incoherent waves. The incoherent waves are associated with zero or near zero heat flux. This suggests that the less coherent waves may be more effective in regulating the electron heat flux, or that the scattering and energization of solar wind electrons by the narrowband waves results in broadening of the waves. The oblique propagation and large amplitudes of both the narrowband and less coherent whistlers enable resonant interactions with electrons over a broad energy range, and, unlike parallel whistlers, do not require that the electrons and waves counter-propagate. Therefore, they are much more effective in modifying solar wind electron distributions than parallel propagating waves.

1. Introduction

The importance of whistler-mode waves in the evolution of solar wind electrons has long been a topic of interest. Most theoretical and simulation studies, as well as observations (Gurnett & Anderson 1977; Neubauer et al. 1977; Lin et al. 1998) have concluded that the whistler-mode waves occur at frequencies of much less than the electron cyclotron frequency, and propagate parallel (or antiparallel) to the solar wind magnetic field. There are only a few observational studies focused on simultaneous measurements of whistler-mode waves and strahl electrons (Gurgiolo et al. 2012; Lacombe et al. 2014; Kajdić et al. 2016), although many examined the consistency of the local or radial dependence of the electrons with theoretical predictions (Feldman et al. 1975; Scime et al. 1994; Graham et al. 2017).

In contrast to these studies, Breneman et al. (2010), using STEREO 3D electric field waveform capture data (time-domain sampler, TDS), discovered very narrowband, large amplitude whistler-mode waves with frequencies of ~0.2 to ~0.4 fₑ, which were most commonly observed in association with stream interaction regions (SIRs), and at much lower rates with interplanetary (IP) shocks. Assuming the cold plasma whistler-mode dispersion relation, wavelengths were estimated to be ~10–25 km (the order of the electron gyroradius), with propagation at angles of 50°–60° (near the resonance cone), and phase velocities of ~700–1200 km s⁻¹ (comparable to the electron Alfven speed). These properties indicate that Doppler shifts are not significant. Electric field amplitudes were 10 s to up to >100 mV m⁻¹, ~1–3 orders of magnitude larger than previously observed in the solar wind, with parallel components as much as 30% of the perpendicular component. Because the STEREO instrument does not have search coil data, the phase velocity and wavevector direction (sunward or antisunward component) of these waves cannot be directly determined. The wave magnetic fields were estimated to be <~1 nT, comparable to the background magnetic field (though we note that the large parallel to perpendicular electric field ratio indicates that the cold plasma dispersion may not be accurate for obtaining wave parameters). Note that Coroniti et al. (1982), using electric and magnetic field spectral data from ISEE-3, concluded that several wave bursts in a similar frequency band with amplitudes of ~0.1–1 mV m⁻¹, observed downstream of interplanetary shocks, were consistent with oblique propagation. Given the limitations of the ISEE-3 instrumentation, the properties of the waves, but not the amplitudes, are comparable to the narrowband whistlers reported by Breneman et al.

Most theoretical studies of instability mechanisms for solar wind whistler-mode waves have focused on either temperature anisotropy (Kennel & Petschek 1966; Gary & Wang 1996) or heat flux instabilities (Forslund 1970; Feldman et al. 1975; Gary et al. 1975; Gary 1978; Shaaban et al. 2018) They have concluded that only parallel propagating waves at low frequencies (~0.01 fₑ) have significant growth rates. Note many of these studies did not cover the range of fₚₑ/fₑ (fₚₑ is the electron plasma frequency) in our data set (~35–60). These mechanisms cannot explain the frequencies and oblique propagation seen in the STEREO data discussed in Breneman et al. or in this study. Several studies of correlated Langmuir
waves and whistler-mode waves (Kennel et al. 1980; Kellogg et al. 1992; Sharma et al. 1992; Ergun et al. 1998) have suggested that either both modes are destabilized by an electron bump-on-tail, or that they may be related by a three-wave decay.

In contrast, the whistler fan instability (Bošková et al. 1992; Krafft & Volokitin 2003), due to the anomalous cyclotron resonance, generates oblique whistler-mode waves in the appropriate frequency range (\(\sim\)tents \(f_{ce}\)). A recent study (Vasko et al. 2019) also examined the whistler fan instability in the context of solar wind core and strahl electrons. Their mechanism could generate obliquely propagating waves of the type reported by Breneman et al. (2010), although Vasko et al. were apparently unfamiliar with the experimental observations of the waves and the associated simulations showing their effectiveness in scattering electrons in the halo and strahl energy range. The instability mechanism is due to strahl electrons, and depends on a number of parameters including the strahl to core density ratio, strahl width, and electron beta. A second proposed mechanism for generating oblique whistler-mode waves is the cyclotron resonance of electron beams with velocities greater than twice the electron Alfvén speed (\(V_{Ae}\)) (Sauer & Sydora 2010). The waves become more oblique as the beam velocity increases relative to \(V_{Ae}\) and waves are damped at high beta.

Several recent studies using ARTEMIS (Tong et al. 2019) or Cluster (Lacombe et al. 2014) data have also shown the existence of whistler-mode waves in this higher frequency band. In contrast to the STEREO results, they find waves that are parallel propagating. Lacombe et al. (2014), using magnetic field spectral data from the Cluster STAFF instrument, found narrowband whistler-mode waves with durations of seconds to several hours. Using events with durations greater than 5 minutes, they concluded that the waves occurred in regions of slow solar wind and low background turbulence, and large electron heat flux, consistent with the whistler heat flux instability, at least for large electron parallel beta. They suggested that the waves could regulate the electron heat flux. A more recent study utilizing ARTEMIS magnetic field waveform data (Tong et al. 2019) also found whistler-mode waves, with occurrence consistent with the heat flux instability. However, they concluded that the amplitudes were too small to have a major role in controlling heat flux. Kajdič et al. (2016) compared electron observations and found that strahl width was broader when narrowband whistlers were observed. Stansby et al. (2016), utilizing electric and magnetic field waveform data from ARTEMIS, determined that large amplitude whistlers had wavelengths dependent on parallel electron beta, and were consistent with the heat flux instability. The waves were propagating parallel to the magnetic field and antisunward, and therefore, could not scatter strahl, in disagreement with other studies.

The Breneman et al. study, which found large amplitude obliquely propagating narrowband whistlers, utilized waveform captures with durations of \(\sim0.12\) s, and thus could not observe the wave packet durations and structure. In this paper, we present a study of STEREO 2.1 s waveform captures, enabling us to, for the first time, determine the packet structure of these waves. In Section 2, we present an SIR with examples of the waves and their relationship to electron parameters. In Section 3, we show statistical results on wave properties, association with solar wind structures, and comparison to characteristics of the electrons. In Section 4, we compare theoretical models to previous studies and discuss the possible importance of these waves for the evolution of solar wind electrons and solar wind structures.

2. Observations of Narrowband Whistlers

Figure 1 presents an example SIR observed by STEREO-A (note that the SIR extended from 2017 March 15 20:00 UT to 2017 March 17 11:00 UT, but no TDS were obtained until about 2017 March 16 08:00 UT). Panel (a) plots the magnetic field in RTN coordinates at 8 samples s\(^{-1}\) (from the IMPACT instrument, Luhmann et al. 2008), panel (b) shows the proton velocity (black) and density (pink) (from PLASTIC, Galvin et al. 2008), panel (c) plots the parallel electron beta, \(\beta_{e||}\) (black) and the electron temperature anisotropy, \(T_{e\perp}/T_{e||}\) (blue), and panel (d) plots the parallel electron heat flux, \(Q_{e||}\). Note that the SWEA data (Sauvaud et al. 2008) that provide the estimates of electron heat flux, beta, and temperature anisotropy only cover electrons from \(\sim50\) eV to 3 keV. Therefore, the temperature anisotropy and heat flux values in all plots are not the total values for these parameters. Because the SWEA instrument does not measure the core electrons, the proton density from PLASTIC was used as a better estimate for total solar wind density. The sample rates for both the PLASTIC data (1 sample minute\(^{-1}\)) and the SWEA data 2 samples minute\(^{-1}\) are much slower than the 2.1 s wave observations. The S/WAVES instrument (Bougeret et al. 2008) takes short bursts of 3D electric field waveforms (TDS) at a commandable set of sample rates and durations with the largest amplitude samples being transmitted. Our study, therefore, is focused on the largest amplitude waves. We show data from the \(\sim7800\) samples s\(^{-1}\), 2.1 s mode, enabling study of the wave packet structure of the narrowband whistler-mode waves. Throughout this SIR, 157 TDS were transmitted, of which 109 (at the times indicated by the gold and blue vertical lines) were whistler-mode waves at frequencies of \(\sim0.2\) \(f_{ce}\), and four were in the ion acoustic frequency range.

In addition to the narrowband coherent whistler-mode waves (gold lines), there are waves at comparable frequencies that are broader in frequency with less coherent waveforms (blue lines), which we label as “incoherent.” Narrowband (“coherent”) waves meet the whistler-mode criteria (right-hand polarized, frequency \(<0.5\ f_{ce}\)) and have very sinusoidal waves forms and frequency bandwidth \(<\sim10\) Hz (see examples in Figures 1(f) and (g)). The bandwidth is defined as two times (maximum frequency at 1/2 maximum power—minimum frequency over at 1/2 maximum power). Incoherent waves meet the whistler-mode criteria, but have bandwidths >11 Hz and less coherent, more irregular waveforms (examples in Figures 1(h) and (i)). Of the 109 whistler waves, 29 met the criteria for coherent, and 80 met the criteria for incoherent. The statistics discussed below will examine these two classes of events separately.

A number of characteristics of the oblique whistler waves and their association with SIRs and plasma parameters are illustrated by the example SIR in Figure 1. The waves are often close-packed. In this SIR, the waves occur primarily within the faster solar wind (>450 km s\(^{-1}\)). The waves are not associated with the intervals of largest temperature anisotropy. Coherent waves are observed over a wider range of \(\beta_{e||}\), and often with larger \(|Q_{e||}|\) than the incoherent waves.
3. Statistical Results

The database for this study comprises all the 2.1 s TDS obtained by STEREO, including the intermittent intervals from STEREO-A and STEREO-B from June through 2011 November, and continuous period on STEREO-A from 2017 March through 2018 January. Whistler-mode waves were identified using a wave mode sorting algorithm based upon one used by Breneman et al. (2010). The algorithm was modified to work effectively on 2.1 s TDS captures, which are longer than the 0.12 s TDS in Breneman et al. Data for the three components of the electric field for each TDS burst were initially Fourier transformed with a sliding window of size 0.1 times the burst duration, with a 50% overlap of successive windows. Each waveform was also analyzed using a sliding autocorrelation function (with the same step size and overlap), used to identify waves with regular periodic behavior. For TDS waveforms with significant power at frequencies \( < f_{ce} \), the FFT output was used to calculate wave bandwidth, and frequency and amplitude at maximum power for each step, and these results were combined with the autocorrelation to calculate a wave quality function, defined at time \( X \) as:

\[
\text{Quality}[x] = 100 \times \frac{\text{AutocorrCoeff}[x]}{\text{Bandwidth}[x]} \times \text{Amplitude}[x] \times \text{MaxPower}[x].
\]

Each waveform (for all three components) had its maximum quality recorded, with values above 2 defining the duration of significant intervals. Intervals below a quality threshold of 2 were not included in the database. The frequency of each wave packet and interval was defined as that identified from the longest duration of the three electric field components. Examination by eye has confirmed that this approach accurately identifies whistler-mode wave properties. The determination that a bandwidth of 10 Hz distinguished between the narrowband coherent waves and the less coherent waves was done by visual inspection. The coherent and incoherent waves do not comprise a bimodal distribution; rather, there is a gradual transition from extremely narrowband coherent waveforms to the more broadband irregular waveforms.

Wave characteristics including spacecraft frame frequency, hodograms in magnetic field-aligned coordinates, coherency, and power spectra were obtained. Using the cold plasma dispersion relation for whistler-mode waves and the electric field hodograms in minimum variance coordinates (polarization), the wavevector angle to the magnetic field, the phase velocity, and the magnetic field perturbation were determined (see Cattell et al. 2008; Breneman et al. 2010 for details). Breneman et al. (2010) showed that Doppler shifts were not significant for these waves. Note that the abnormally large ratio
of parallel to perpendicular electric field indicates that the warm plasma dispersion relation would be more accurate. The SIRs, interplanetary coronal mass ejections (ICMEs), and IP shocks identified using the criteria described in Jian et al. (2018, 2019) were obtained from the STEREO Level 3 lists (https://stereossc.nascom.nasa.gov/pub/ins_data/impact/level3/).

Histograms of the wave characteristics are shown in Figure 2, with the left-hand panels referring to the narrowband (coherent) and the right-hand panels to the less coherent (incoherent) whistler-mode waves. Figures 2(a) and (b) plot the wave frequency normalized to the electron cyclotron frequency ($f/f_{ce}$); Figures 2(c) and (d) plot the wave amplitude, based on the largest perpendicular component (less than total amplitude due to the large obliquity); and Figures 2(e) and (f) plot the wave normal angle with respect to the solar wind magnetic field. The average $f/f_{ce}$ is $\sim 0.2$ for both; however, the width is broader for the incoherent waves, as expected since these were are defined by their broader frequency and less coherent waveforms. The average amplitudes for the incoherent waves is slightly larger ($\sim 12$ mV m$^{-1}$) than for the coherent ($\sim 9$ mV m$^{-1}$). Note that the maximum observed amplitudes were $\sim 70$ mV m$^{-1}$.

Both coherent and incoherent waves are highly oblique (average of $64^\circ$ for coherent and $58^\circ$ for incoherent), propagating near the resonance cone (beyond which the waves cannot propagate) with the associated significant electric fields parallel to the background magnetic field. This enables resonant interactions with electrons over a wide energy range without requiring counter-propagation. The duration of individual wave packets peaks at $\sim 0.1–0.2$ s ($\sim 10$ s of wave periods), but extends to $\sim 1.8$ s. The average is slightly longer ($\sim 0.7$ s) for coherent waves compared to incoherent waves ($\sim 0.5$ s). These results are consistent with Breneman et al. (2010); however, they only studied the coherent waves, and, because they used 0.12 s TDS, they could not determine packet durations. The two classes of waves have comparable properties, with the exception of bandwidth and waveform coherence and a small difference in average propagation angle. The fact that the classes are not disjoint suggests that the observed differences are associated with wave growth and saturation mechanisms.

The occurrence of whistler-mode waves within SIRs and ICMEs is shown in Figure 3, which plots the number of events versus normalized time in the structure with $t = 0$ signifying the start of the structure and $t = 1$ the end of the structure. Both coherent and less coherent waves are seen throughout SIRs and ICMEs, with somewhat more in the first half to two-thirds of an event. The occurrence rate of coherent waves with respect to incoherent waves is higher in SIRs. The percentage of SIRs and of ICMEs that have these high frequency whistler-mode waves is summarized in Table 1. During the time period when STEREO-A was continuously in the 2.1 s TDS mode, there were 54 SIRs and 9 ICMEs; 68% of the SIRs had coherent whistler groups (defined as two or more waves separated by no more than 10 minutes, and an average wave density greater than or equal to one wave per minute). Of the nine ICMEs, 33% had coherent groups. The coherent whistlers are more common in SIRs that ICMEs (consistent with Breneman et al. 2010). However, when we include both coherent and incoherent whistlers, we find that 76% of SIRs, and 67% of ICMEs had whistler groups. For the 34 interplanetary (IP) shocks, three had whistler wave groups within 30 minutes of the shock ramp for a 9% occurrence rate (not shown). Most were seen in the ramp or within $\sim 6$ minutes in the downstream region. The low rate is consistent with Breneman et al., and the specific association with the ramp is consistent with Cohen et al. (2019). Note that only 1 out of 54 SIRs and 1 out of 9 ICMEs did not contain at least one whistler wave (respectively, 98% and 89% had whistlers); however, 15 of 34 IP shocks did not have whistlers ($\sim 55%$ had whistlers).

The relationships of the waves to solar wind plasma parameters including electron beta, temperature anisotropy, and heat flux, and solar wind speed provide important clues to the instability mechanisms, and the effect of the waves on solar wind electrons. Because the SWEA instrument does not measure the core electrons, the proton density (at a lower cadence of once/minute than the electron measurements) was used as a better estimate for total solar wind density in the calculations of beta. The magnetic field data are at 8 samples s$^{-1}$. Figures 4(a) and (b) shows the dependence of wave occurrence on electron temperature anisotropy ($T_{e\perp}/T_{e\parallel}$) versus parallel electron beta ($\beta_{e\parallel}$). The upper red line is the whistler temperature anisotropy threshold, $T_{e\perp}/T_{e\parallel} = 1 + 0.27/\beta_{e\parallel}^{0.57}$ and the lower red line is an arbitrary firehose instability (both from Lacombe et al. 2014, based on Gary et al. 1999). Note that these thresholds are based on the total temperature anisotropy, whereas the anisotropy we plot is associated only with suprathermal electrons. The contours indicate the density of observed whistler-mode waves. There is no clear distinction between the two wave types. Although wave occurrence is constrained by the thresholds for the whistler temperature anisotropy and the firehose instabilities, neither mechanism is consistent with observed wave properties. No relationship between the amplitude of waves and the temperature anisotropy ($T_{e\perp}/T_{e\parallel}$) was found for either wave type. Most waves occurred when $T_{e\perp}/T_{e\parallel} < 1$ (see Table 2).

Earlier studies (Lacombe et al. 2014) found that coherent parallel propagating whistler-mode waves occurred within the quiet, slow solar wind. The occurrence distribution is centered around $\sim 450$ km s$^{-1}$ (Table 2) for the oblique waves, but significant numbers of wave packets occur in association with solar wind speeds above 600 km s$^{-1}$.

The dependence of wave occurrence on heat flux and parallel electron beta is plotted in Figure 4(c) for coherent and Figure 4(d) for incoherent waves. The threshold for the heat flux instability from Gary et al. (1999) is overplotted in green ($0.5/\beta_{e\parallel}^{0.8}$). Only 11% of the coherent waves and 6% of the incoherent waves are above this threshold. The orange line is the upper limit from Lacombe et al. (2014) for their parallel propagating whistler-mode waves. It is interesting to note that only 2 of the oblique waves in our study are above this orange line. The dependence on the parallel heat flux, $Q_{e\parallel}$, and the total heat flux are distinctly different for the coherent and incoherent waves, in contrast to the dependence on temperature anisotropy. The number of coherent wave events has a broad peak around 0.006–0.01 erg cm$^{-2}$ s$^{-1}$, and extends to higher $\beta_{e\parallel}$; however, the occurrence of less coherent waves (4(d)) peaked near 0 erg cm$^{-2}$ s$^{-1}$, and primarily $\beta_{e\parallel} < \sim 0.5$. Figure 5 presents histograms for wave occurrence versus total electron heat flux for the coherent (panel (c)) and incoherent (panel (d)) waves, and confirms the difference in association with heat flux between the two wave types. Table 2 summarizes the average values of total heat flux and total beta for both wave types. The very clear difference suggests several possible conclusions: (1) the less coherent waves are more effective at regulating the electron heat flux; (2) the less coherent waves are associated with a different instability mechanism; or (3) there are nonlinear processes that relate the
Figure 2. Histograms of wave properties for coherent (left panels) and incoherent (right panels) whistler-mode waves. (a) and (b) $f/f_{ce}$; (c) and (d) amplitude; (e) and (f) wave angle with respect to $B$. 

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coherent and less coherent wave types. Note there is no clear dependence of wave amplitude on heat flux.

The bottom panel of Figure 6(c) plots, for the event shown in Figure 1, the energy corresponding to twice the electron Alfvén speed, \(E_{\text{Ae}}\) (black) and dotted lines corresponding to the center energy of SWEA channels (from \(\sim 400\) to \(\sim 1100\) eV). The locations of coherent waves are overplotted in gold and of incoherent whistler-mode waves in blue. Most of the narrowband (coherent) waves occur when \(E_{\text{Ae}}\) is lower than for most incoherent waves. The next set of panels plot pitch angle distributions for SWEA energy bands centered on \(\sim 400\) eV (6(a)), \(650\) eV (c), and \(1057\) eV (b). All the coherent waves are associated with strahl up to center energy of \(1067\) eV, above the highest \(E_{\text{Ae}}\) of \(\sim 650\) eV. In contrast, incoherent waves are seen in regions where there is no strahl or the strahl is at energies below \(E_{\text{Ae}}\), which ranges from \(\sim 1057\) to \(\sim 1820\) eV. The average of three STE detectors (D1–D3), plotted in 6(a), shows that there were not significant electron fluxes at higher energies. Panel 6(a) also plots the electron (from SWEA; blue) and ion (from PLASTIC; red) temperatures. The whistler waves occur in association with higher ion temperatures, possibly indicating that they heat the ions or that the conditions required for wave instability are correlated with higher ion temperatures.

The statistical dependence of wave occurrence on \(E_{\text{Ae}}\) is shown in Figure 5(a) for coherent and Figure 5(b) for incoherent whistlers. As in the specific example shown in Figure 6, coherent waves are more likely to occur when \(E_{\text{Ae}}\) is lower than for incoherent waves. The average \(E_{\text{Ae}}\) is \(\sim 175\) eV for coherent waves, and \(\sim 474\) eV for incoherent waves. This suggests that lower energy beams are needed to produce the narrowband waves. Since strahl in this energy range is more commonly observed, the threshold for the beam mechanism will more often be met than for the more incoherent waves. Sauer & Sydora (2010) also found that the waves became more oblique as the beam energy increased with respect to \(E_{\text{Ae}}\).

There is a tendency for the wave angle to increase as average \(E_{\text{Ae}}\) decreases. Both the dependence of wave occurrence and of wave angle on \(E_{\text{Ae}}\) are consistent with this beam driven mechanism. A more detailed comparison would require determining the peak energy of the electrons observed at the time of the waves, and whether there is evidence for beam distributions, which we cannot include in this study due to limitations imposed by the STEREO electron instruments.

The whistler fan instability, associated with the heat flux due to the suprathermal strahl, has also been shown to destabilize very oblique whistler-mode waves. The dependence of wave occurrence on a proxy for the ratio of the electron heat flux normalized by \(Q_0 = 1.5N_0m_ec^2v_e^3\) (where \(N_0\) is the core density approximated by the proton density and \(v_e\) is the core speed) versus total electron beta is shown in Figure 7, left panel (coherent) and right panel (incoherent). Due to the limitations of the SWEA instrument, we do not know the core speed, so the value from Wilson et al. (2019) is used. The orange line is the linear instability threshold from Equation (5) (Vasko et al. 2019), which depends upon the ratio of strahl width to the speed of the core electrons. Based on the studies of Štverák et al. (2009) and Wilson et al. (2019), a value of 2.0 is used for this ratio. The total number of coherent whistler wave packets is 1810, and there were only 184 (\(\sim 10\%\)) above this threshold (orange line). Of the 2704 incoherent whistler packets, only 39 (\(\sim 1\%\)) were above the threshold. Given the assumptions needed to obtain values for the normalized heat flux and total electron beta, the close relationship between wave occurrence and threshold is very striking. The good correlation indicates that the fan instability is consistent with the STEREO observations.

### Table 1
Association of Whistler-mode Wave Groups with Solar Wind Structures

|       | Coherent Wave Group | Any Wave Group | \(\geq 1\) Whistor |
|-------|---------------------|----------------|------------------|
| SIRs  | 54                  | 68%            | 76%              | 98%             |
| ICMEs | 9                   | 33%            | 67%              | 89%             |
| IP Shocks | 34               | 9%             | 9%               | 55%             |

Figure 3. Superposed epoch analysis of the occurrence of whistler waves in stream interaction regions (left) and interplanetary coronal mass ejections (right). Start time of each structure = 0; end time = 1.
4. Discussion and Conclusions

The results of the first statistical study of the STEREO 2.1 s waveform capture 3D electric field data have shown that both very narrowband (coherent, bandwidth <10 Hz) whistler-mode waves (originally identified by Breneman et al. 2010) and less coherent (bandwidth >11 Hz) are very common in SIRs, less common in ICMEs, and rare in association with IP shocks. Both wave types have average frequencies of $\sim 0.2 f_{ce}$, and are quasi-electrostatic, propagating near the resonance cone ($\sim 65^\circ$ for coherent and $60^\circ$ for incoherent), with significant electric fields parallel to the interplanetary magnetic field. This enables resonant interactions with electrons over a wide energy range without requiring counter-propagation. Mean amplitudes are slightly larger for the less coherent wave packets ($\sim 12 \text{ mV m}^{-1}$) than for the narrowband waves ($\sim 9 \text{ mV m}^{-1}$); peak values for both reach $\sim 70 \text{ mV m}^{-1}$.

Although STEREO does not have a search coil magnetometer, the magnetic perturbation can be estimated using the cold plasma dispersion relation. Values are often the order of the background solar wind magnetic field, although the highly oblique propagation and significant electric field parallel to the solar wind field indicates that the warm dispersion relation would be more accurate.

Table 2
The Mean, Median, and Mode Values of Electron Parameters and Solar Wind Speed for the Set of Narrowband (Coherent) and Incoherent Whistler-mode Waves

|                      | Coherent (Mean; Median; Mode) | Incoherent (Mean; Median; Mode) |
|----------------------|-------------------------------|----------------------------------|
| Temperature Anisotropy | 0.92; 0.92; 0.90               | 0.82; 0.83; 0.90                 |
| Total Heat Flux, erg cm$^{-2}$s$^{-1}$ | 0.012; 0.010; 0.008 | 0.011; 0.008; 0.00 |
| Total Beta            | 0.77; 0.70; 0.50               | 0.39; 0.32; 0.25                 |
| Solar Wind Speed, km s$^{-1}$ | 427; 402; 385                | 440; 394; 326                    |

Figure 4. Wave occurrence for electron temperature anisotropy vs. parallel beta for (a) coherent and (b) incoherent wave packets. Upper red line is the whistler temperature anisotropy threshold, $T_e/T_i = 1 + 0.27/\beta_{pe}^{-0.57}$ and the lower red line is an arbitrary firehose instability (both from Lacombe et al. 2014, based on Gary et al. 1999). Wave occurrence for normalized electron heat flux vs. parallel beta for (c) coherent and (d) incoherent wave packets. Lower green line is the heat flux instability threshold from Gary et al. (1999) and the upper orange line is the upper bound found by Lacombe et al. (2014). Note that temperatures and heat flux are obtained from electrons with energies from $\sim 50$ eV to $\sim 3$ kev, and beta is calculated from the proton density (a better measure of total density) and electron temperature for electrons from $\sim 50$ eV to $\sim 3$ kev.

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The fact that the waves described herein are oblique could be due to propagation effects since whistlers propagating in an inhomogeneous medium can refract toward the resonance cone; however, the fact that the oblique waves are significantly larger amplitude than found in studies of parallel propagating waves in the solar wind makes this a very unlikely explanation. The distribution of wave angles, and the fact that waves are often observed in regions without strong inhomogeneity also contradict this explanation.

Earlier observational studies based on spectral data (Gurnett & Anderson 1977; Neubauer et al. 1977; Coroniti et al. 1982; Lin et al. 1998) found generally low amplitudes (1–3 orders of magnitude smaller than we show), likely due to the long time averages and limited frequency resolution. We showed that packet durations are usually <1 s, shorter than the time resolution of older wave instruments. The waves are also very narrowband, which would result in underestimates of wave amplitudes from spectral data.

The dependence of wave occurrence and amplitudes on $T_{e\perp}/T_{e\parallel}$, $Q_e$, $\beta_e$, and $E_{\text{Ae}}$ was compared to theories of instability mechanisms and to previous results. No relationship was found between the amplitude of waves and the temperature anisotropy ($T_{e\perp}/T_{e\parallel}$) for either wave type. Most waves occurred when $T_{e\perp}/T_{e\parallel} < 1$. Although wave occurrence as a function of the electron temperature anisotropy and parallel beta is constrained by the thresholds for the whistler temperature anisotropy and the firehose instabilities, neither mechanism is consistent with observed wave properties.

By comparing our observations to thresholds the whistler heat flux fan instability associated with the suprathermal strahl (Vasko et al. 2019), we show, for the first time, that both the narrowband coherent waves and the less coherent waves are consistent with this mechanism, although more coherent waves occur above the threshold (Figure 7). The fact that the less coherent waves occur on average with zero or low heat flux (Figure 5(d)) suggests that the less coherent waves may better regulate the electron heat flux than the coherent waves, and that there is some evolutionary process connecting the two wave types. The narrowband waves are also consistent with the electron beam driven instability proposed by Sauer & Sydora (2010). The less coherent waves, on average, are associated with much higher electron Alfvén speeds, without higher energy beams, and are not consistent with the beam driven mechanism. Given the similarity in the wave properties and the
fact that the coherent and incoherent waves are not two distinct populations, it seems unlikely that the instability mechanisms for the two are different. The observed differences are more likely due to wave evolution and saturation mechanisms.

There have been several studies focused on higher frequency (∼0.02 to ∼0.5 \( f_{ce} \)) whistler-mode waves in the solar wind, using data from Cluster, ARTEMIS, or Wind. The Cluster and ARTEMIS statistical studies all found parallel propagating whistlers consistent with the heat flux instability, and, therefore, did not focus on the wave modes described in our study. Lacombe et al. (2014), in a study of 10 minute intervals in the free solar wind utilizing primarily 4 s spectral data from the Cluster STAFF instrument, found narrowband parallel propagating whistler-mode waves, lasting for intervals of >∼5 minutes. For large parallel electron beta, wave occurrence fell along the heat flux instability threshold. The waves occurred in the quiet slow (<500 km s\(^{-1}\)) solar wind, in association with high electron heat flux. Also using Cluster data, Kajdič et al. (2016) showed that whistler-mode waves (at ∼0.1 \( f_{ce} \) and propagating within 20° of the magnetic field) observed in pristine, and primarily slow, solar wind resulted in significant broadening of strahl electrons, when compared to intervals without waves. The effect was energy dependent and largest for energies of ∼50 times the electron thermal energy.

Stansby et al. (2016) analyzed several whistler electric and magnetic field waveforms obtained in the ARTEMIS burst

Figure 6. Electron data and Alfvén energy for SIR in Figure 1. (a) Energy spectrogram of the average of the three STE detectors; ion temperature overplotted in red; electron temperature in green. Note that the scale for temperatures (on the right) is linear and different from electron energy (on the left). (b) Pitch angle distribution for SWEA energy bands centered on (b) 1057 eV, (c) 650 eV, and (d) 400 eV. (e) The energy corresponding to twice the electron Alfvén speed, \( E_{Ae} \), (black) and dotted lines corresponding to the center energy of SWEA channels (from ∼400 to ∼1100 eV). The locations of coherent whistler wave packets are overplotted in gold; incoherent whistler packets are overplotted in blue.

Figure 7. Occurrence of coherent (left) and incoherent (right) whistler waves for normalized electron heat flux vs. beta. The orange line is the linear instability threshold from Equation (5) (Vasko et al. 2019) for the parameter 2.0 in their Table 1. Note that the heat flux is obtained from electrons with energies from ∼50 eV to ∼3 kev, and beta is calculated from the proton density (a better measure of total density) and electron temperature for electrons from ∼50 eV to ∼3 kev.
mode. The wave electric field amplitudes ($<\sim 0.2$ mV m$^{-1}$) were an order of magnitude below our amplitude threshold ($\sim 3$ mV m$^{-1}$). Use of both electric and magnetic fields enabled the determination of the wave propagation direction, which was magnetic field aligned and antisunward; thus the waves they observed cannot interact resonantly with the antisunward strahl. Wave properties were consistent with the whistler cold dispersion relation, but the dependence on the parallel electron beta was consistent with the warm dispersion relation. Tong et al. (2019), utilizing magnetic field spectral data (once every 8 s) from ARTEMIS, also concluded that the whistlers were parallel propagating, primarily observed in slow solar wind, and small amplitude ($f_{ce}B_{0}/k_{\parallel} < 0.02$). Occurrence was strongly dependent on the electron temperature anisotropy. The beta dependence of $f/f_{ce}$ was found to be consistent with the heat flux instability, and $T_{e\perp}/T_{e\parallel} > 1$ was also required. This is not consistent with our results that show most events occur when $T_{e\perp}/T_{e\parallel} < 1$. Note that the ARTEMIS plasma instrument extends to low energies, so the temperature anisotropy included core electrons, whereas our STEREO measurement were restricted to $\sim 50$ eV to $\sim 3$ keV. Although this could account for the different dependence, it is more likely that the waves are different modes, consistent with the different wavevector directions. Simulations of the heat flux instability (Kuzichev et al. 2019) found that the nonlinear development was consistent with ARTEMIS and Cluster observations.

Several event studies utilizing Wind (TDS) waveform data reached different conclusions. Ergun et al. (1998), in a study of solar Type III radio bursts, showed that the observed electron distributions peaked at $\sim 9$ keV were marginally unstable to both oblique, quasi-electrostatic whistlers and to Langmuir waves. They suggested that these oblique waves might play an important role in the evolution of flare-accelerated electrons and other solar wind electrons. This idea is consistent with our results; however, we do not have pitch angle distributions extending to such high energies, and most wave packets were not associated with significant fluxes at energies $>2$ keV (energy range of the STE detector). In another study of Type III radio bursts, Moullard et al. (1998) observed whistler-mode waves, in this case parallel propagating, and also suggested either a beam driven or wave decay mechanism. Associated with a magnetic cloud, Moullard et al. (2001) observed parallel propagating whistlers ($0.3-0.5 f_{ce}$). The observed waves were small amplitude ($0.1-0.4$ mV m$^{-1}$, and $dB \sim 0.2$ nT), and occurred when there was an enhanced loss-cone distribution in hot electrons. They concluded that both the whistlers and the simultaneously observed Langmuir wave packets could be excited by the loss-cone distribution. They also speculate that the whistlers might be associated with decay of the Langmuir waves, while stating that this would likely require oblique whistlers. Although this mechanism may operate at times, it cannot explain the whistlers we observed, which were not associated with Langmuir waves.

To summarize, large amplitude, highly oblique whistler-mode waves are commonly observed in the solar wind. The waves are observed over a wide range of solar wind speeds, up to 700 km s$^{-1}$. We have shown, for the first time, that both the narrowband coherent waves and the less coherent waves are consistent with the heat flux fan instability. Only the narrowband waves are consistent with the electron beam instability. The fact that the less coherent waves occur with zero or low heat flux suggests that they may be more effective in regulating the electron heat flux, or that the scattering and energization of solar wind electrons by the narrowband waves results in broadening of the waves. The highly oblique propagation and large amplitudes of both the narrowband and less coherent whistlers enable resonant interactions with electrons over a broad energy range, and, unlike parallel whistlers, do not require that the electrons and waves counter-propagate.

We thank the STEREO PLASTIC Investigation (A.B. Galvin, PI) and NASA grant NNX15AU01G, the IMPACT investigation (J. Luhmann, PI), and B. Lavraud and the SWEA team. The work at the University of Minnesota was supported by NASA grants NNX16AF80G, 80NSSC19K305, and NNX14AK73G. SPEDAS software (courtesy of Space Science Laboratory, UC Berkeley) was utilized.

**References**

Bošková, J., Třiska, P., Omelchenko, Y. A., et al. 1992, SoGG, 36, 177
Bougeret, J.-L., Goertz, K., Kaiser, M. L., et al. 2008, SSRv, 136, 487
Breneman, A., Cattell, C., Schreiner, S., et al. 2010, JGRA, 115, A08104
Cattell, C., Wygant, J. R., Goertz, K., et al. 2008, GeoRL, 35, L01105
Cohen, Z. A., Cattell, C. A., Breneman, A. W., et al. 2019, arXiv:1909.08176
Coroniti, F. V., Kennel, C. F., Scarf, F. L., & Smith, E. J. 1982, JGR, 87, 6029
Ergun, R., Larson, D., Lin, R. P., et al. 1998, ApJ, 505, 435
Feldman, W. C., Ashbridge, J. R., Bame, S. J., Montgomery, M. D., & Gary, S. P. 1975, JGR, 80, 4181
Forslund, D. W. 1970, JGR, 75, 17
Gary, A. B., Kistler, L. M., Popecki, M. A., et al. 2008, SSRv, 136, 437
Gary, S. P. 1978, JGR, 83, 2504
Gary, S. P., Feldman, W. C., Forslund, D. W., & Montgomery, M. D. 1975, JGR, 80, 4197
Gary, S. P., Neagu, E., Skoug, R. M., & Goldstein, B. E. 1999, JGR, 104, 19843
Gary, S. P., & Wang, J. 1996, JGR, 101, 10749
Graham, G. A., Rae, I. J., Owen, C. J., et al. 2017, JGRA, 122, 3858
Gurgiolo, C., Goldstein, M. L., Vilas, A. F., & Fazakerley, A. N. 2012, AnGeo, 30, 163
Gurnett, D. A., & Anderson, R. R. 1977, JGR, 82, 632
Jian, L. K., Luhmann, J. G., Curtis, W., & Galvin, A. B. 2019, SoPh, 294, 31
Jian, L. K., Russell, C. T., Luhmann, J. G., & Galvin, A. B. 2018, ApJ, 885, 114
Kadić, P., Alexandrova, O., Maksimovic, M., Lacombe, C., & Fazakerley, A. N. 2016, ApJ, 833, 172
Kellogg, P. J., Goertz, K., Lin, N., et al. 1992, GeoRL, 19, 1299
Kennef, C. F., & Petschech, H. E. 1966, JGR, 71, 1
Kennef, C. F., Scarf, F. L., Coroniti, F. V., et al. 1980, GeoRL, 7, 129
Kraft, C., & Volokitin, A. 2003, AnGeo, 21, 1393
Kuzichev, I. V., Vasko, I. Y., Soto-Chavez, A. R., et al. 2019, ApJ, 882, 81
Lacombe, C., Alexandrova, O., Matteini, L., et al. 2014, ApJ, 796, 5
Lin, N., Kellogg, P. J., MacDowall, R. J., et al. 1998, JGR, 103, 12023
Luhmann, J. D., Curtis, W., Schroeder, P., et al. 2008, SSRv, 136, 117
Moullard, O., Burgess, D., Salem, C., et al. 2001, JGR, 106, 8301
Moullard, O., Krasnoselskikh, V., Tong, Y., et al. 2019, ApJL, 871, L29
Neubauer, F. M., Musmann, G., & Dehmel, G. 1977, JGR, 82, 3201
Neubauer, F. M., Musmann, G., & Dehmel, G. 1977, JGR, 82, 3201
Omelchenko, Y. A., et al. 1992, StGG, 36, 177
Shaaban, S. M., Lazar, M., & Poedts, S. 2018, MNRAS, 480, 310
Sharma, R. P., Tripathi, Y. K., Al Janabi, A. H., & Boswell, R. W. 1992, JGR, 97, 4275
Stansby, D., Horbury, T. S., Chen, C. H. K., & Matteini, L. 2016, ApJL, 829, L16
Šveřák, Š., Maksimovic, M., Trávníček, P., et al. 2009, JGR, 114, A05104
Tong, Y., Vasko, I. Y., Artemyev, A. V., Bale, S. D., & Mozer, F. S. 2019, ApJ, 878, 41
Vasko, T., Krásovská-vák, V., Tong, Y., et al. 2019, ApJL, 871, L29
Wilson, L. B., III, Chen, L.-J., Wang, S., et al. 2019, ApJS, 245, 24