Statistical Study of Whistler Waves in the Solar Wind at 1 au

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Abstract

Whistler waves are intermittently present in the solar wind, while their origin and effects are not entirely understood. We present a statistical analysis of magnetic field fluctuations in the whistler frequency range (above 16 Hz) based on about 801,500 magnetic field spectra measured over 3 yr aboard the Artemis spacecraft in the pristine solar wind. About 13,700 spectra (30 hr in total) with intense magnetic field fluctuations satisfy the interpretation in terms of quasi-parallel whistler waves. We provide estimates of the whistler wave occurrence probability, amplitudes, frequencies, and bandwidths. The occurrence probability of whistler waves is shown to strongly depend on the electron temperature anisotropy. The whistler wave amplitudes are in the range from about 0.01 to 0.1 nT and typically below 0.02 of the background magnetic field. The frequencies of the whistler waves are shown to be below an upper bound that is dependent on $\beta_e$. The correlations established between the whistler wave properties and local macroscopic plasma parameters suggest that the observed whistler waves can be generated in local plasmas by the whistler heat flux instability. The whistler wave amplitudes are typically small, which questions the hypothesis that quasi-parallel whistler waves are capable of regulating the electron heat flux in the solar wind. We show that the observed whistler waves have sufficiently wide bandwidths and small amplitudes, so that effects of the whistler waves on electrons can be addressed in the frame of the quasi-linear theory.

Key words: instabilities – plasmas – solar wind – waves

1. Introduction

Whistler waves, electromagnetic emissions between ion and electron cyclotron frequencies, are potentially regulating several fundamental processes in the collisionless or weakly collisional solar wind. In particular, spacecraft observations of the electron heat flux values below a threshold dependent on $\beta_e$, were interpreted in terms of the heat flux regulation by the whistler heat instability (WHFI; Feldman et al. 1975, 1976; Scime et al. 1994; Gary et al. 1999; Tong et al. 2018) and whistler fan instability (Vasko et al. 2019). The observed radial evolution of the angular width of the suprathermal field-aligned electron population (strahl electrons) in the solar wind (e.g., Hammond et al. 1996; Graham et al. 2017) requires pitch-angle scattering that can be potentially provided by whistler waves (Vocks et al. 2005; Shevchenko & Galinsky 2010; Vocks 2012; Kajdič et al. 2016; Vasko et al. 2019). Whistler waves may also suppress the electron heat flux in collisionless or weakly collisional astrophysical plasma (Pistinner & Eichler 1998; Gary & Li 2000; Roberg-Clark et al. 2016, 2018; Komarov et al. 2018). The necessity of a heat flux suppression mechanism is suggested by observations of the temperature profile of hot gases in galaxy clusters (e.g., Cowie & McKee 1977; Bertschinger & Meiksin 1986; Zakamska & Narayan 2003; Wagh et al. 2014; Fang et al. 2018). The understanding of whistler wave origins and effects requires statistical analysis of whistler wave occurrence and properties in the solar wind.

The magnetic field fluctuations with power-law spectra in various frequency ranges are persistently observed in the solar wind and referred to as turbulence (see, e.g., Bruno & Carbone 2013, for review). Early studies associate the magnetic field turbulence in the whistler frequency range with whistler waves, and their power was shown to decrease with increasing radial distance from the Sun and enhance around interplanetary shocks and high-speed stream interfaces (e.g., Beinroth & Neubauer 1981; Coroniti et al. 1982; Lengyel-Frey et al. 1996; Lin et al. 1998). However, later studies show that the whistler frequency range of the magnetic field turbulence is dominated by kinetic Alfvén and slow ion-acoustic waves Doppler-shifted into the whistler frequency range (e.g., Bale et al. 2005; Salem et al. 2012; Chen et al. 2013; Lacombe et al. 2017). The whistler wave contribution to the magnetic field turbulence spectrum is still under debate (e.g., Gary 2015; Narita et al. 2016; Kellogg et al. 2018).

The modern spacecraft measurements have recently shown that whistler waves are intermittently present in the pristine (not disturbed by shocks or Earth’s foreshock) solar wind (Lacombe et al. 2014; Stansby et al. 2016; Tong et al. 2019). Whistler waves have been identified by a local peak superimposed on a power-law spectrum of the magnetic field turbulence background. Therefore, these whistler waves should be produced by kinetic instabilities (free energy in the plasma), rather than by the turbulence cascade (see Gary 2015, for discussion). In addition to the pristine solar wind, whistler waves have been reported around interplanetary shock waves (e.g., Breneman et al. 2010; Wilson et al. 2013) and in Earth’s foreshock (e.g., Hoppe & Russell 1980; Zhang et al. 1998).

The focus of this paper is the statistical analysis of whistler waves produced by kinetic instabilities in the pristine solar wind. The detailed analysis of whistler waves in the pristine solar wind has become possible only recently owing to simultaneous wave and particle measurements aboard the Cluster and Artemis spacecraft (Lacombe et al. 2014; Stansby et al. 2016; Tong et al. 2019). In contrast to the Wind and Stereo spacecraft, wave measurements aboard Cluster and Artemis are available almost continuously, rather than triggered by high-amplitude events,
which typically occur around interplanetary shocks (e.g., Breneman et al. 2010; Wilson et al. 2013). Lacome et al. (2014) have selected about 20 10-minute intervals with whistler wave activity observed aboard Cluster in the pristine solar wind. The analysis of the magnetic field cross-spectra has shown that whistler waves propagate quasi-parallel to the background magnetic field. The simultaneous measurements of the electron heat flux have been presented to argue that the whistlers waves are produced by the WHFI (see, e.g., Gary et al. 1994, for the WHFI theory). Stansby et al. (2016) have selected several 10-minute intervals of Artemis measurements to test the whistler wave dispersion relation in dependence on $\beta$. Tong et al. (2019) have carried out a detailed analysis of wave and particle measurements for Stansby et al. (2016) events and demonstrated that the whistler waves were produced locally on a timescale of seconds and indeed by the WHFI. The analysis by Tong et al. (2019) has proved that the WHFI may indeed operate in the solar wind and clearly demonstrated the critical role of the electron temperature anisotropy; the parallel temperature anisotropy may quench the WHFI instability, while the perpendicular temperature anisotropy favors the instability onset.

In spite of some recent progress, the parameters controlling the occurrence and properties of whistler waves in the solar wind have not been considered on a statistical basis. In this paper we present analysis of several hundred days of Artemis observations in the solar wind (two spacecraft orbiting the Moon, see Angelopoulos 2011, for details). The whistler wave selection produced a data set of about 13,700 whistler wave spectra (>30 hr in total) in the pristine solar wind, which is the most representative data set to date. The paper is organized as follows. We describe instrument characteristics, methodology, and data selection criteria in Section 2. The results of the statistical study are presented in Sections 3–5. We discuss the statistical results in light of whistler wave generation mechanism, electron heat flux regulation, and recent particle-in-cell simulations in Section 6. The conclusions are summarized in Section 7.

2. Data and Methodology

We use Artemis spacecraft measurements from 2011 to 2013 and select observations in the pristine solar wind, which is excluding Earth’s foreshock and the lunar wake. The Search Coil Magnetometer instrument provides fast Fourier transform magnetic field spectra with 8 s cadence and covers 64 piecewise linearly spaced frequency channels between 8 and 4096 Hz (Roux et al. 2008). We use the spectral power density $SPD_\parallel$ of the magnetic field in the spacecraft spin plane (almost ecliptic plane), the spectral power density $SPD_\perp$ of the magnetic field component along the spin axis (almost perpendicular to the ecliptic plane), and the total spectral power density $SPD = SPD_\parallel + 2 SPD_\perp$. The Flux Gate Magnetometer provides the quasi-static magnetic field measurements at 4 vectors per second (Auster et al. 2008), which we downsample by averaging to 8 s cadence of the magnetic field spectra. The electron velocity distribution function (VDF) is measured every 3 s by the Electrostatic Analyzer (McFadden et al. 2008) and transmitted to the ground every 3 or 96 s depending on the telemetry mode. We use the ground-calibrated particle moments (density, bulk velocity, and temperatures) and the electron heat flux parallel to the magnetic field computed by integrating the electron VDF:

$$q_e = \frac{1}{2} m_e \int (v|| - \langle v|| \rangle) (v - \langle v \rangle)^2 VDF(v) \, dv,$$

where $m_e$ is the electron mass, $v||$ is the electron velocity parallel to the magnetic field, and $\langle v \rangle$ is the electron bulk velocity. The particle moments available at 96 s are upsampled to 8 s cadence of the magnetic field spectra via the linear interpolation. In total we have analyzed 801,527 magnetic field spectra, spanning 1803 hr and 359 days in 2011–2013.\(^7\) In the rest of this paper, we will refer to each magnetic field spectrum as an independent event. Note that we did not filter out interplanetary shocks, but looking through the list of interplanetary shocks observed on Wind,\(^8\) we found only several days in our data set with listed shocks. Therefore, our data set is dominated by observations in the pristine solar wind. In what follows, we clarify criteria for whistler wave selection and demonstrate the data analysis techniques.

Figure 1 presents the magnetic field spectrum and particle moments for a particular day (2011 July 29) in our data set. Panel (a) shows the total spectral power density from 16 to 300 Hz. The SPD enhancements between 20 and 60 Hz appear first around 14:25 UT and continue intermittently thereafter before about 16:30 UT. In terms of a local electron cyclotron frequency $f_{ce}$, the observed SPD enhancements are between 0.1$f_{ce}$ and 0.3$f_{ce}$, which is in the whistler frequency range. The wave activity can be characterized by the total magnetic field power in the frequency range between 16 and 300 Hz.

$$P_B \equiv \int_{16 \text{ Hz}}^{300 \text{ Hz}} SPD(f) \, df. \quad (2)$$

Panel (b) demonstrates that $P_B$ well traces the SPD enhancements. In the absence of clear wave activities, $P_B$ is a mixture of the inherent turbulence background and instrument noise between 16 and 300 Hz. We divide the magnetic field spectra into 2 hr chunks and define the background power $P_{eg}$ as the 20th percentile of $P_B$ within every chunk. Panel (c) presents $P_B/P_{eg}$, demonstrating thereby that the wave activity corresponds to $P_B$ significantly exceeding $P_{eg}$. The amplitude of magnetic field fluctuations associated with the wave activity is characterized by $B_{so} = (P_B - P_{eg})^{1/2}$. Panel (d) shows that the amplitude of the magnetic field fluctuations reaches 0.05 nT, while $B_{so}/B_{eg}$, which is the amplitude of the magnetic field fluctuations with respect to the background magnetic field, does not exceed 0.01. We emphasize that $B_{so}$ is the amplitude averaged over 8 s, while the actual peak amplitude may be larger owing to the intermittent appearance of the magnetic field fluctuations over 8 s. Panels (e) to (h) present a few plasma parameters: $\beta_e = 8 \pi n_e T_e/|B_0|^2$, $T_e/T_\parallel$ is the electron temperature anisotropy, $q_e/q_0$ is the electron heat flux normalized to the free-streaming heat flux $q_0 = 1.5 \pi n_e T_e (2T_e/m_e)^{1/2}$, and $v_{sw}$ is the solar wind proton velocity. In the above

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\(^5\) Ground-calibrated particle moments are accessed via two data products, THB_L2_ESA and THC_L2_ESA, which can be found in https://cdaweb.gsfc.nasa.gov/.

\(^6\) The electron VDF is accessed from http://themis.ssl.berkeley.edu/data/themis/ and then processed by the open-source SPEDAS software (Angelopoulos et al. 2019).

\(^7\) The data intervals are provided in https://doi.org/10.5281/zenodo.2652949.

\(^8\) www.cfa.harvard.edu/shocks/wi_data
parameters, $n_e$ is the electron density, $T_{e\perp}$ and $T_{e\parallel}$ are the perpendicular and parallel electron temperature, and $B_0$ is the magnitude of the quasi-static magnetic field. Note that we have used a natural unit system in which temperature has the units eV. The Boltzmann constant is dropped throughout the paper.

Visual inspections of the magnetic field spectra from our data set show that SPD enhancements in the whistler frequency range are always below 300 Hz. The wave power $P_B$ in the frequency range between 16 and 300 Hz is found to be a good indicator of the wave activity. The spectral power density in the first (8 Hz) frequency channel is excluded from $P_B$ computation, because it provides strong and noisy contribution to $P_B$, so that the wave activity at $f \gtrsim 16$ Hz could not be identified in $P_B$. Another reason for excluding the first channel is that it is more likely to be contaminated by low-frequency magnetic field fluctuations different from whistler waves (see below). Visual inspections show that $P_B > 3P_g$ is a reasonable empirical criterion for selecting noticeable wave activities between 16 and 300 Hz and filtering out spectra corresponding to variations of the turbulence background. The criterion $P_B > 3P_g$ selects 17,050 magnetic field spectra, which is about 38 hr and about 2% of the original data set.

Although the selected wave activities are in the whistler frequency range, they do not necessarily represent whistler waves (see Section 1 for discussion). The routinely available $Artemis$ measurements include only two components of spectral power densities, which is not sufficient to determine wavevectors and polarizations of the selected wave activity events. Nevertheless, these components, namely, spectral power densities $SPD_{\perp}$ and $SPD_{\parallel}$, along with results of the

![Figure 1](image_url)

**Figure 1.** Wave activity in the whistler frequency range observed aboard $Artemis$ on 2011 July 29 (1 day from our data set). (a) Magnetic field spectral power density; 0.1$f_c$, and 0.3$f_c$, are indicated with blue and red curves, respectively, where $f_c$ is a local electron cyclotron frequency. (b) Magnetic field power $P_B$ in the frequency range between 16 and 300 Hz determined by Equation (2). (c) Magnetic field power $P_B$ normalized to the background turbulence power $P_g$ determined every 2 hr as the 20th percentile of $P_B$; the visual inspection of our data set showed that $P_B > 3P_g$ (dashed line) is a reasonable criterion for selecting the wave activity events in the whistler frequency range and filtering out variations of the turbulence background. (d) Amplitude of magnetic field fluctuations evaluated as $B_w = (P_B - P_g)^{1/2}$ (red trace) and $B_w/B_0$ (black trace), which is the amplitude with respect to the local background magnetic field $B_0$. (e–h) $\beta_e = 8\pi n_e T_e/B_0^2$, electron heat flux $q_e$ normalized to the free-streaming heat flux $q_0 = 1.5n_eT_e(2T_e/m_e)^{1/2}$, and solar wind velocity $v_{sw}$. 

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previous observations, enable us to filter out events contradicting the whistler wave interpretation and provide a basis to argue that the major part of the selected events are whistler waves. The technique relies on the previous analysis of the magnetic field spectral matrix (spectra and cross-spectra up to 400 Hz) measurements provided by Cluster (Lacombe et al. 2014) and the analysis of magnetic field waveforms (frequencies up to 64 Hz resolved) provided by Artemis (Stansby et al. 2016; Tong et al. 2019), which both showed that whistler waves in the pristine solar wind propagate quasi-parallel to the background magnetic field $B_0$. The observations of quasi-parallel whistler waves are consistent with theoretical predictions of potential instabilities operating in the solar wind (Gary et al. 1994, 2012). Oblique whistler waves may be present in the solar wind, but they are predicted to be electrostatic and, hence, not identifiable in the magnetic field spectra (Vasko et al. 2019).

The whistler wave propagation parallel to the magnetic field results in a specific relation between SPD$ _h $ and SPD$ _f $, that is dependent on $B_0$ orientation with respect to the spin axis (see Figure 2 for schematics). A whistler wave at frequency $f$ propagating parallel to $B_0$ is a circularly polarized wave with the magnetic field along $b_1 \cos(2\pi ft) + b_2 \sin(2\pi ft)$, where $b_{1,2}$ are unit vectors in the plane perpendicular to $B_0$. This wave would produce $SPD_h(f) \propto \sin^2 \chi$ and $SPD_f(f) \propto (1 + \cos^2 \chi)/2$, where $\chi$ is the angle between $B_0$ and the spin axis (Figure 2), so that the ratio

$$R = \frac{SPD_h(f)}{SPD_f(f)}$$

would equal $R_0 = 0.5 \sin^2 \chi$. A reasonable agreement between the observed $R$ and expected $R_0$ may allow filtering out events corresponding to plasma modes different from quasi-parallel whistler waves.

Figure 3 presents the analysis of the nature of the wave activity shown in Figure 1. Panel (a) presents angle $\chi$ (Figure 2) computed using the quasi-static magnetic field measurements. Panels (b) and (c) present SPD$ _h $ and SPD$ _f $. For every magnetic field spectrum with $P_B > 3P_g$, we identify the frequency channel $f_w$ with the largest total spectral power density, SPD in Figure 1(a), and compute $R$ using SPD$ _h (f_w)$ and SPD$ _f (f_w)$ in Equation (3). Panel (d) shows that $R$ is well consistent with $R_0 = 0.5 \sin^2 \chi$, supporting thereby the interpretation of the wave activity in terms of quasi-parallel whistler waves.

Figure 4 presents results of the comparison between $R$ and $R_0$ evaluated for all 17,050 magnetic field spectra with $P_B > 3P_g$. Panel (a) shows that $R/(R + R_0)$ are clustered around 0.5, that is, $R \approx R_0$. Most of the events with $R/(R + R_0)$ significantly deviating from 0.5 are in the three lowest-frequency channels at 16, 24, and 32 Hz, where low-frequency modes are expected most likely to appear owing to the Doppler effect. Panel (b) shows that the events with $R/(R + R_0)$ significantly deviating from 0.5 have frequencies from 0.02$f_{ce}$ to 0.5$f_{ce}$, demonstrating thereby that the whistler frequency range may be populated by plasma modes different from quasi-parallel whistler waves. We introduce a quantitative criterion $0.4 < R/(R + R_0) < 0.6$ to select the events not contradicting the interpretation of quasi-parallel whistler waves. The probability and cumulative distribution functions in panels (c) and (d) show that this selection criterion filters out about 20% of the events, leaving about 13,700 magnetic field spectra. In accordance with Lacombe et al. (2014), this shows that whistler waves identified in the magnetic field spectra in the pristine solar wind are predominantly quasi-parallel. In what follows we use the selected 13,700 events to clarify how the occurrence and properties of whistler waves depend on macroscopic plasma parameters.

The selected whistler wave SPD enhancements spread over several frequency channels. To quantify the frequency bandwidth of the whistler waves, we determine first the background spectral power density SPD$ _a (f)$ at frequency $f$ as the 20th percentile of SPD$ (f)$ at that frequency every 2 hr. Similarly to $P_g$, SPD$ _a (f)$ is a combination of the magnetic field turbulence background and intrinsic instrument noise level. The whistler wave spectrum SPD$ (f)$–SPD$ _a (f)$ is fitted to the Gaussian model with the peak at $f_w$,

$$SPD(f) - SPD_a(f) = A \exp \left[ -\frac{(f - f_w)^2}{2\sigma^2} \right],$$

where $A$ and $\sigma$ are the best-fit parameters. The frequency bandwidth $\Delta f$ is estimated as the FWHM,

$$\Delta f = 2\sigma(2 \ln 2)^{1/2} \approx 2.35 \sigma.$$

Figure 5 presents the analysis of the frequency bandwidth of a particular whistler wave spectrum with the peak at $f_w \sim 40$ Hz measured at 15:35:33 UT on 2011 July 29 (one spectrum from Figure 1). The whistler wave SPD enhancement is about two orders of magnitude larger than SPD$ _a (f_w)$. The Gaussian fit to SPD$ (f)$–SPD$ _a (f)$ yields the frequency bandwidth $\Delta f \sim 21$ Hz. We restrict the statistical analysis of the frequency bandwidth to whistler wave events with $f_w > 16$ Hz, because only in those events could we guarantee that the peak of the Gaussian is at $f_w$, rather than at some frequency below 16 Hz. The criterion $f_w > 16$ Hz leaves 5800 spectra for the frequency bandwidth analysis, which is 42% of the selected 13,700 whistler wave spectra.

3. Whistler Wave Occurrence

Out of about $8 \times 10^5$ spectra, we have associated about 13,700 spectra with quasi-parallel whistler waves, which yields

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**Figure 2.** Schematics of the Artemis search coil magnetometer antennas. The instrument provides spectral power densities SPD$ _h $ and SPD$ _f $ of magnetic field fluctuations along the spacecraft spin axis and in the plane perpendicular to the spin axis. The total spectral power density (Figure 1(a)) of the magnetic field fluctuations is computed as SPD = SPD$ _h $ +2 SPD$ _f $. For a whistler wave propagating parallel to the quasi-static magnetic field $B_0$ there is a particular relation between SPD$ _h $ and SPD$ _f $ that depends on angle $\chi$ (see Section 2 for details).
The occurrence probability of whistler waves depends on macroscopic plasma parameters. We emphasize that this is the probability of sufficiently intense whistler waves ($P_B > 3 P_e$) above 16 Hz, i.e., whistler waves that are less intense and at lower frequencies have been excluded. The overall occurrence of whistler waves in the pristine solar wind is certainly higher. We demonstrate below that the occurrence probability of the selected whistler waves depends on macroscopic plasma parameters.

Figure 6 presents the analysis of effects of the electron heat flux $q_e/q_0$ and $\beta_e$ on the occurrence probability of whistler waves. Panel (a) shows the distribution of all $\sim 8 \times 10^5$ magnetic field spectra in the ($q_e/q_0$, $\beta_e$) parameter plane. The electron heat flux at $\beta_e \gtrsim 1$ is below a threshold $q_e/q_0 \sim 1/\beta_e$ that is in agreement with previous spacecraft observations (Gary et al. 1999; Tong et al. 2018). This heat flux threshold was previously considered as the evidence for the heat flux regulation by the WHFI (Feldman et al. 1976; Gary et al. 1999). Panel (b) shows the distribution of $\sim 13,700$ magnetic field spectra associated with quasi-parallel whistler waves. Combining the distributions shown in panels (a) and (b), we evaluate the occurrence probability of whistler waves at various ($q_e/q_0$, $\beta_e$). Panel (c) shows that the occurrence probability does not favor the parameter space near the threshold $q_e/q_0 \sim 1/\beta_e$ and, instead, somewhat enhances at low heat flux values.

Figure 7 presents the analysis of effects of the electron heat flux $q_e/q_0$ and electron temperature anisotropy $T_{e\perp}/T_{e\parallel}$ on the whistler wave occurrence probability. Panels (a) and (b) present...
distributions of all events and whistler wave events in the \((q_e/q_0, T_{\perp}/T_{\parallel})\) parameter plane. In accordance with previous statistical studies (e.g., Štverák et al. 2008; Artemyev et al. 2018), solar wind electrons at 1 au most often exhibit parallel temperature anisotropy, \(T_{\parallel}/T_{\parallel} < 1\). Panels (a) and (b) are combined to compute the occurrence probability in the \((q_e/q_0, T_{\perp}/T_{\parallel})\) parameter plane. Panel (c) clearly demonstrates that the temperature anisotropy quite critically affects the whistler wave occurrence probability. At any given \(q_e/q_0\) the occurrence probability increases with increasing \(T_{\perp}/T_{\parallel}\). The occurrence probability is less than a few percent at \(T_{\perp}/T_{\parallel} \lesssim 1\) but increases up to 10\%–60\% at \(T_{\perp}/T_{\parallel} > 1\). In addition, panel (b) shows that for whistler waves to occur the temperature anisotropy should be above a threshold that increases as the electron heat flux decreases: at \(q_e/q_0 \lesssim 10^{-2}\) the temperature anisotropy should be above 0.75, while at \(q_e/q_0 \gtrsim 3 \times 10^{-2}\) whistler waves may occur at \(T_{\perp}/T_{\parallel}\) as low as 0.5. In addition to the 2D occurrence probabilities, we have computed whistler wave occurrence probabilities in dependence on individual macroscopic plasma parameters.

Figure 8 presents the occurrence probability of whistler waves in dependence on \(q_e/q_0, \beta_e, v_{sw},\) and \(T_{\perp}/T_{\parallel}\). The occurrence probability \(P(\xi)\) of whistler waves in dependence on a macroscopic plasma parameter \(S\) is determined as \(P(\xi) = N_W(\xi)/N(\xi)\), where \(N_W(\xi)\) is the number of whistler wave events with \(S\) in the range \((\xi - \Delta\xi/2, \xi + \Delta\xi/2)\), while \(N(\xi)\) is the total number of events with \(S\) in the same range. The bin width \(\Delta\xi\) is chosen so that the number of events within each bin would be sufficiently large. The uncertainties of \(P(\xi)\) are estimated with the assumption that each particle measurement is independent.\(^9\) Panels (a), (c), and (d) demonstrate that the electron heat flux, \(\beta_e\), and solar wind velocity do not significantly affect the occurrence probability of whistler waves. Panel (b) confirms that the whistler wave occurrence probability is critically dependent on the electron temperature anisotropy. The probability is less than 2\% at \(T_{\perp}/T_{\parallel} < 0.9\) but increases from 5\% to 15\% as \(T_{\perp}/T_{\parallel}\) varies from 0.95 to 1.2.

4. Whistler Wave Intensity

Figure 9 presents the probability distribution functions of whistler wave amplitudes \(B_w\) and \(B_w/B_0\) for the slow \((v_{sw} \lesssim 400\) km s\(^{-1}\)\) and fast \((v_{sw} > 500\) km s\(^{-1}\)\) solar wind. Our data set is dominated by the slow solar wind events; fast solar wind events constitute less than 12\% of the data set. Panels (a) and (b) show that whistler wave amplitude \(B_w\) is typically below 0.02\(B_0\) or in physical units ranging from 0.01 up to 0.1 nT. We recall that \(B_w\) is the amplitude averaged over 8 s, so that the actual peak amplitudes of magnetic field fluctuations could be in principle larger owing to the intermittent presence of whistler waves over 8 s. However, these amplitudes are consistent with previous measurements of whistler waveforms aboard the Artemis spacecraft (Stansby et al. 2016; Tong et al. 2019), indicating thereby that quite likely whistler waves in the pristine solar wind have amplitudes \(B_w\) much smaller than \(B_0\). Panels (a) and (b) also demonstrate that there is a bit higher chance to observe intense whistler waves in the slow solar wind than in the fast solar wind.

Figure 10 presents the distribution of the averaged whistler wave amplitude \((B_w/B_0)\) in the \((q_e/q_0, \beta_e)\) and \((T_{\perp}/T_{\parallel}; q_e/q_0)\) parameter planes. Panel (a) demonstrates that \((B_w/B_0)\) is strongest when both \(\beta_e\) and \(q_e/q_0\) are high. As a result, the averaged whistler wave amplitude is enhanced in the parameter space around the threshold \(q_e/q_0 \sim 1/\beta_e\). It is interesting to note that the whistler wave occurrence probability does not favor this region in the parameter space (Figure 6). The reason is that the occurrence of whistler waves is most critically controlled by the temperature anisotropy, rather than \(q_e/q_0\) or \(\beta_e\). Panel (b) shows that \((B_w/B_0)\) enhances with increasing \(T_{\perp}/T_{\parallel}\) at fixed \(q_e/q_0\), while the positive correlation between \((B_w/B_0)\) and \(q_e/q_0\) is noticeable only at \(T_{\perp}/T_{\parallel} \gtrsim 1\).

Figure 11 presents the distribution of whistler wave amplitudes \(B_w/B_0\) in dependence on individual macroscopic parameters. The top panels indicate the mean and median \(B_w/B_0\) values in dependence on \(q_e/q_0, T_{\perp}/T_{\parallel}, \beta_e,\) and \(v_{sw}\), while the shaded regions cover from the 25th percentile to the 75th percentile of \(B_w/B_0\). The bottom panels present the number of events within bins used to compute the \(B_w/B_0\) distributions in the top panels. Panels (a) and (b) show that the mean and median values of \(B_w/B_0\) are positively correlated with \(q_e/q_0\) and \(T_{\perp}/T_{\parallel}\), though the overall variation of these values is about 30\%. The negative correlation between \(B_w/B_0\) and the heat flux at \(q_e/q_0 \gtrsim 0.3\) is likely a physical effect, because the number of events in the corresponding bins is sufficiently large. Panel (c) shows that the median and mean values of \(B_w/B_0\) are most strongly correlated with \(\beta_e\), both values increase by about a factor of three as \(\beta_e\) increases from 0.1 to 5. Panel (d) shows that the whistler wave amplitude is negatively correlated with the solar wind velocity, varying by a factor of two from the slow to fast solar wind.

5. Whistler Wave Frequency

5.1. Observations

We consider the frequency channel \(f_n\) with the largest SPD \((f)\) or largest enhancement \(\text{SPD}(f) = \text{SPD}(f) - \text{SPD}\) \((f)\) (both provide the same frequency channel) as the frequency of a whistler wave.

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\(^9\) Assuming that each particle measurement has the same probability to have a whistler companion, and that \(n\) measurements estimate the probability to be \(p\). Then, the standard error of \(p\) is \(s_p = \sqrt{p(1 - p)/n}\). We estimate the uncertainty of \(p\) as the uncertainty at the 95\% level of confidence \(2s_p = 2\sqrt{p(1 - p)/n}\).
event. We could consider the frequency channel with the largest relative SPD enhancement, \( \text{SPD}(f) / \text{SPD}(g) \), as the whistler wave frequency estimate. Because \( \text{SPD}(g) \) is a monotonically decreasing function of the frequency, this approach provides frequencies higher than \( f_w \), but we have found that the difference is less than 50%. We use \( f_w \) as the whistler wave frequency estimate, while the use of the other frequency would not affect any of our conclusions. We have found that among various macroscopic plasma parameters only \( \beta_e \) correlates strongly with the normalized frequency \( f_w / f_{ce} \).

Figure 12 demonstrates that there are apparent upper and lower frequency bounds that decrease with increasing \( \beta_e \). Below we compare these bounds to theoretical predictions of the WHFI. To quantify the negative correlation between the upper bound on \( f_w / f_{ce} \) and \( \beta_e \), we bin all the whistler wave events according to \( \beta_e \) and select 10% of the highest-frequency events within each bin. These highest-frequency events are fitted to a power law of \( \beta_e \). The best fit (black curve) shown in Figure 12 demonstrates that we generally have \( f_w / f_{ce} \approx 0.24 \beta_e^{-0.31} \). The whistler wave frequencies in Figure 12 are measured in the spacecraft frame and differ from those in the plasma frame by the Doppler shift, \( \Delta f_D = k v_{sw} / 2\pi \), where \( k \) is the whistler wavevector. We have estimated the Doppler shift for all whistler wave events using the wavevector estimate from the cold dispersion relation, \( f f_{kd} / (c^2 + k^2 d_e^2) \), where \( d_e = c / \omega_{pe} \) is the electron inertial length and \( \omega_{pe} \) is the electron
plasma frequency (e.g., Stix 1992). We have found that $\frac{\Delta f_D}{f_w}$ is less than 0.3, so that the measured frequency can be considered as a good estimate of the whistler wave frequency in the plasma frame.

Figure 13 presents the frequency bandwidth $\Delta f$ of about 5800 whistler wave events with $f_w > 16$ Hz. Panel (a) shows that $\Delta f$ is typically about 15 Hz, though it can be as large as 50 Hz. Panel (b) shows that the frequency bandwidth normalized to the whistler wave frequency $f_w$ is typically in the range between 0.1 and 1. There is a clear positive correlation between $\frac{\Delta f}{f_w}$ and $\beta_e$: at $\beta_e \ll 1$ whistler waves typically exhibit $\frac{\Delta f}{f_w} \sim 0.2$, while $\frac{\Delta f}{f_w}$ is typically about 0.5 at $\beta_e \sim 1$. The
implications of the frequency width estimates will be discussed in Section 6.

5.2. WHFI Predictions

The linear theory of the WHFI suggests that the electron VDF consisting of bi-Maxwellian core and halo populations, counterstreaming in the plasma rest frame, can be unstable to whistler wave generation at sufficiently large core and halo bulk velocities (Gary et al. 1975, 1994). Tong et al. (2019) have recently shown for several events that the WHFI indeed generates whistlers waves in the pristine solar wind. In this section we evaluate the maximum and minimum frequencies of whistler waves expected to be produced by the WHFI in dependence on $\beta_e$. We consider the simplest electron VDFs consisting of isotropic core and halo populations ($T_c = T_h$) and assume a zero net electron current in the plasma rest frame, $n_c\Delta v_c + n_h\Delta v_h = 0$, where $n_{c,h}$ and $\Delta v_{c,h}$ are densities and bulk velocities of the core and halo populations. Because the bulk velocities are much smaller than the corresponding thermal velocities (e.g., Feldman et al. 1975; Tong et al. 2019), we have $\beta_e \approx \beta_c + \beta_h$, where $\beta_e = 8\pi n_e T_e/B_0^2$, $\beta_h = 8\pi n_h T_h/B_0^2$, and $T_{c,h}$ are core and halo temperatures.

The linear growth rate of the WHFI normalized to $f_e$ depends on $n_e/n_0$, $T_h/T_e$, $T_p/T_e$, and $\Delta v_c/v_A$, where $n_0$ is the total electron density (which is also assumed equal to the proton density), $T_{c,h}$ are the core and the halo temperatures, $T_p$ is the proton temperature, $v_A = B_0/(4\pi n_0 m_p)^{1/2}$ is the Alfvén velocity, and $m_p$ is the proton mass. The growth rate is almost independent of the proton-to-core electron temperature ratio, because in realistic conditions protons do not resonate with whistler waves produced by the WHFI (Gary et al. 1975). In what follows we keep $T_p/T_e = 1$, which is a reasonable assumption at 1 au (e.g., Newbury et al. 1998; Artemyev et al. 2018). To evaluate the maximum and minimum frequencies of whistler waves that can be generated by the WHFI instability, we fix $\beta_e$ and vary $n_e/n_0$, $T_h/T_e$, and $\Delta v_c/v_A$ in the ranges typical for the solar wind at 1 au (Table 1). For each combination of these three parameters we compute the linear growth rate using the numerical code developed by Tong et al. (2015) and identify the frequency of the fastest-growing whistler wave. Then, for each fixed $\beta_e$ we identify the maximum and minimum frequencies of whistler waves that can be generated by the WHFI. At a fixed $\beta_e$ the minimum frequency decreases with decreasing threshold value on the growth rate. Different threshold values result in different minimum frequency bounds, but these bounds are of similar shape and almost parallel to each other in the $(\beta_e, f/f_e)$ plane. The maximum and minimum frequency bounds are well fitted to modified power laws,

$$f f_e = a(\beta_e + b)^{c}. \tag{5}$$

Table 2 presents the best-fit parameters $a$, $b$, and $c$ for the maximum frequency bound at zero growth rate and for the minimum frequency bounds derived for several growth rate thresholds, $\gamma/\omega_A > 10^{-5}$ and $10^{-6}$, where $\omega_A = 2\pi f_A$.

Figure 12 overlays the theoretical maximum and minimum frequency bounds upon the measured whistler wave frequencies. The presented minimum frequency bound is derived for $\gamma/\omega_A > 10^{-6}$. The frequencies of the major part of the observed whistler waves fall between the minimum and the maximum theoretical bounds, demonstrating thereby that the observed whistler waves could be in principle generated by the WHFI. Moreover, the generation can be local, that is, the whistler waves are generated in a local plasma, rather than generated in some other region and propagated to the spacecraft location.

6. Discussion

We have carried out statistical analysis of whistler waves observed in the pristine solar wind using the most representative data set collected up to date. We have focused on whistler waves identified by a local peak in the spectral power density of the magnetic field fluctuations, which is why these whistler waves are produced by free energy in a plasma, rather than by the turbulence cascade. Out of 801,527 magnetic field spectra measured at 1 au aboard Artemis, we have selected about 17,050 intense wave activity events in the whistler frequency range and associated 13,700 of them with quasi-parallel whistler waves. Thus, about 80% of the intense events in the whistler frequency range are consistent with quasi-parallel whistler wave interpretation. This conclusion is in agreement with results of the previous less extensive studies of waveform and cross-spectra measurements (Lacombe et al. 2014; Stansby et al. 2016; Tong et al. 2019). The other ~20% of the intense events are highly likely low-frequency plasma modes.
Doppler-shifted into the whistler frequency range, because they are predominantly observed in the three lowest-frequency channels. The overall occurrence of quasi-parallel whistler waves in our data set is about 1.7%, but the actual occurrence of whistler waves is certainly higher, because we selected only sufficiently intense whistler waves above 16 Hz.

We have shown that the occurrence probability of whistler waves most critically depends on the electron temperature anisotropy. There is not any drastic dependence of the whistler wave occurrence on the electron heat flux, solar wind velocity, or \( \beta_e \). The occurrence probability is less than 2\% when \( T_e/\sigma T_e \| \lesssim 0.9 \), but it varies from 5\% to 15\% as \( T_e/\sigma T_e \| \) increases from 0.95 to 1.2. This correlation is consistent with the recent analysis by Tong et al. (2019) of several whistler wave events measured in the burst mode (waveform available) aboard Artemis. Tong et al. (2019) have shown that whistler waves in those events were generated locally by the WHFI, while the temperature anisotropy of the halo population \( T_h/\sigma T_h \| \) critically affects the instability onset: \( T_h/\sigma T_h \| \) sufficiently smaller than unity quenches the instability, while \( T_h/\sigma T_h \| > 1 \) significantly enhances the growth rate. In the present statistical analysis we did not compute temperature anisotropies of the core and halo electron populations, but we expect that the increase of the full anisotropy \( T_e/\sigma T_e \| \) corresponds to the increase of the halo temperature anisotropy, because temperature anisotropies of core and halo populations are positively correlated (Feldman et al. 1976; Pierrard et al. 2016).

We have shown that whistler waves in the solar wind have amplitudes \( B_w \) typically below 0.02\( B_0 \) or in physical units below 0.1 nT. These amplitude estimates are consistent with the previous less extensive studies, where waveform measurements were analyzed (Lacombe et al. 2014; Stansby et al. 2016; Tong et al. 2019), but more extensive waveform analysis should be carried out in the future to verify this result. The averaged whistler wave amplitude \( B_w/\sigma B_0 \) is found to be negatively correlated with the solar wind velocity. The average \( B_w/\sigma B_0 \) correlates positively with the electron heat flux and electron temperature anisotropy, but the strongest positive correlation is found with \( \beta_e \). The variation of \( q_e/\sigma q_0 \) and \( T_e/\sigma T_e \| \) over the observed range results in variation of \( B_w/\sigma B_0 \) by about 30\%, while the variation of \( \beta_e \) from 0.1 to 5 results in variation of \( B_w/\sigma B_0 \) by a factor of three. The presented amplitude estimates and correlations between \( B_w/\sigma B_0 \) and macroscopic parameters should be useful for future theoretical studies of the origin and effects of whistler waves in the solar wind. At the moment, we note that the whistler wave amplitudes observed at 1 au are much smaller than whistler wave amplitudes \( B_w \sim B_0 \) reported in recent particle-in-cell simulations (Roberg-Clark et al. 2016, 2018), indicating thereby that the simulations are initialized with electron VDFs unrealistic for the solar wind at 1 au. The fact that the whistler wave amplitudes are rather small calls into question their role in the electron heat flux regulation in the solar wind, though this question deserves a separate study.

We have estimated the frequencies of the observed whistler waves and bandwidths of the whistler wave spectra. The only electrons that can drive and efficiently interact with quasi-parallel whistler waves are those in the first normal cyclotron resonance (e.g., Shklyar & Matsumoto 2009),

\[
\nu_\| = \frac{\omega - \omega_{ce}}{k},
\]

where \( \nu_\| \) is electron velocity parallel to the quasi-static magnetic field, \( \omega = 2\pi f \), \( \omega_{ce} = 2\pi f_{ce} \), and \( k \) is the whistler wavenumber. The minimum energy of the cyclotron resonant electrons (e.g., Kennel & Petschek 1966)

\[
E_R = \frac{B_0^2}{8\pi n_0} \frac{f_{ce}}{f} \left(1 - \frac{f}{f_{ce}}\right)^3,
\]

where we have used the cold dispersion relation of whistler waves, \( f/f_{ce} = k^2d^2 / (1 + k^2d^2) \) (e.g., Stix 1992). Figure 14 presents the minimum resonant energy evaluated using Equation (7) with whistler wave frequencies adopted from

![Figure 13](image_url)
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Figure 14. Minimum energy of electrons to be in the first normal cyclotron resonance with the observed whistler waves. It is given by Equation (7), with the whistler wave frequencies adopted from Figure 12(a). Panel (a) presents the minimum resonant energy in physical units, while panel (b) presents this energy with respect to the electron temperature $T_{\text{el}}$. The averaged resonant energies are presented by the red curves.

Figure 12(a). The minimum resonant energy is negatively correlated with $\beta_e$, because $E_\text{R} \propto B_0^2$, while $\beta_e \propto 1/B_0^2$. Panel (a) shows that the minimum resonant energy is of a few tens of eV at $\beta_e \sim 1$ and above a few hundred eV at low $\beta_e$. Panel (b) shows that in terms of thermal energies the resonant energy is about $3T_e$ at $\beta_e \sim 1$ and a few tens of $T_e$ at low $\beta_e$. We conclude that the observed quasi-parallel whistler waves should be driven by the halo electron population in accordance with previous theoretical (Gary et al. 1975, 1994) and experimental (Tong et al. 2019) studies.

The estimated bandwidths of the whistler wave spectra allow us to evaluate whether the effect of the observed whistler waves on electrons could be addressed within the quasi-linear theory (QLT; e.g., Sagdeev & Galeev 1969). The QLT is applicable for a sufficiently wide frequency width of a whistler wave spectrum (e.g., Karpman 1974): $\Delta f/f_w > (B_w/B_0)^{1/2} (v_{pe}/\omega_{pe})^{1/2}$, where $v_{pe}$ is the electron velocity perpendicular to the magnetic field. Because the whistler waves interact efficiently with halo electrons, we can assume that $v_{pe}$ is a few times larger than the electron thermal velocity. Using the cold dispersion relation for whistler waves, we rewrite the QLT applicability criterion:

$$\frac{\Delta f}{f_w} > \left(\frac{B_w}{B_0}\right)^{1/2} \left(\frac{v_{pe}}{1 - f_w/f_{ce}}\right)^{1/4}. \quad (8)$$

Figure 15 presents the test of the QLT applicability and shows that $\Delta f/f_w$ is always above the right-hand side of Equation (8). The inset panel shows the probability distribution function of the ratio of $\Delta f/f_w$ to the right-hand side and confirms that in the majority of the events $\Delta f/f_w$ is about five times larger than the right-hand side. We conclude that the QLT is likely a good approximation for analysis of effects of the observed whistler waves on electrons. At the same time, we stress that an extensive statistical analysis of waveform measurements should be carried out in the future to verify that whistler wave amplitudes $B_w$ inferred from 8 s magnetic field spectra do not significantly underestimate the actual peak amplitudes of whistler waves. The statement of the QLT applicability concerns only whistler waves in the pristine solar wind. Whistler waves observed in interplanetary shock waves may be rather narrowband and large-amplitude for the QLT to be applicable (e.g., Breneman et al. 2010; Wilson et al. 2013).

Figure 16 presents order-of-magnitude estimates of the quasi-linear relaxation time of unstable electron VDFs by the observed whistler waves. The relaxation time is given by the following expression (e.g., Karpman 1974):

$$\tau \approx \frac{1}{2\pi \omega_p \beta_e} \left(\frac{\Delta f}{f_w}\right)^3 \frac{B_0^2}{B_w^2}.$$

where in deriving this formula we have assumed that $f_w \ll f_{ce}$. The typical relaxation time is a few tens of minutes at low $\beta_e$ to about a minute at $\beta_e \sim 1$. In principle, the relaxation can be as fast as a few seconds. The strong negative correlation between $\tau$ and $\beta_e$ is due to explicit dependence of $\tau$ on $\beta_e$ according to Equation (9) and due to a strong positive correlation between $B_w/B_0$ and $\beta_e$. During the relaxation time whistler waves may cover spatial distances of a few tens of thousands of kilometers, implying that low-frequency density and magnetic field fluctuations may affect the relaxation process of the WHFI.
Finally, we notice that whistler waves considered in this paper are electromagnetic waves that have been identified in the magnetic field spectra. We have definitely missed electrostatic whistler waves potentially present in the solar wind (Vasko et al. 2019) but not visible in the magnetic field spectra. The results of this statistical study will be useful for the future analysis of whistler wave origin and effects, e.g., heat flux regulation and suprathermal electron scattering, in the solar wind.

7. Conclusion

In this section we summarize the results of our statistical analysis of whistler waves at 1 au:

1. The intense wave activity in the whistler frequency range is shown to be dominated (80%) by quasi-parallel whistler waves. The overall occurrence of quasi-parallel whistler waves in the pristine solar wind is found to be about 1.7%. We emphasize that only intense whistler waves above 16 Hz have been considered in this study, so that the actual occurrence is certainly higher.

2. The occurrence probability of whistler waves in the pristine solar wind is strongly dependent on the electron temperature anisotropy $T_{\perp}/T_{\parallel}$. The occurrence probability is less than 2% at $T_{\perp}/T_{\parallel} \lesssim 0.9$ but varies from 5% to 15% as $T_{\perp}/T_{\parallel}$ increases from 0.95 to 1.2. There is no apparent dependence of the whistler wave occurrence on the electron heat flux $q_e/q_0$, the solar wind velocity $v_{sw}$, or $\beta_e$.

3. Whistler waves in the solar wind have amplitudes typically below 0.02$B_0$, where $B_0$ is the magnitude of the quasi-static magnetic field. In physical units the amplitudes are in the range from about 0.01 to 0.1 nT.

4. The average normalized whistler wave amplitude $B_w/B_0$ correlates positively with $q_e/q_0$ and $T_{\perp}/T_{\parallel}$, but the strongest positive correlation is found with $\beta_e$. The variation of $q_e/q_0$ and $T_{\perp}/T_{\parallel}$ over the observed range results in variation of $B_w/B_0$ by about 30%, while variation of $\beta_e$ from 0.1 to 5 results in variation of $B_w/B_0$ by a factor of three. The whistler wave amplitude negatively correlates with the solar wind velocity, varying by a factor of two from slow to fast solar wind.

5. Whistler wave frequencies $f_w/f_e$ fall between some upper and lower bounds dependent on $\beta_e$. The upper bound on the whistler wave frequency is approximately given by $0.24\beta_e^{-0.31}$. The frequency bandwidth $\Delta f/f_w$ of the whistler waves is determined, and $\Delta f/f_w$ is shown to be positively correlated with $\beta_e$.

6. We show that the observed whistler wave frequencies are consistent with the theoretical predictions of the WHFI, indicating thereby that whistler waves in the pristine solar wind can be generated by the WHFI. The generation of some of the whistler waves by the TAI cannot be ruled out.

7. We have shown that the frequency width of the whistler waves is sufficiently wide that the QLT is likely applicable to describe effects of the whistler waves on electrons. The typical quasi-linear relaxation time in a uniform plasma would be from a minute at $\beta_e \sim 1$ to a few tens of minutes at low $\beta_e$. In principle, the relaxation can be as fast as a few seconds.
We have estimated the energies of electrons resonating the whistler waves and shown that the whistler waves should be driven by suprathermal electrons, whose minimum energy $E_R$ is negatively correlated with $\beta_e$. $E_R$ is about a few tens of eV, or equivalently, about three times the thermal energy at $\beta_e \sim 1$, and about a few hundred eV or about 10 times the thermal energy at low $\beta_e$.

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