Occurrence rate of ultra-low frequency waves in the foreshock of Mercury increases with heliocentric distance

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Studies of Mercury’s foreshock have analyzed in detail the properties of ultra-low frequency waves. However, an open question remains in regards to understanding favorable conditions for these planetary foreshocks waves. Here, we report that 0.05–0.41 Hz quasi-monochromatic waves are mostly present under quasi-radial and relatively low intensity Interplanetary Magnetic Field, based on 17 Mercury years of MESSENGER Magnetometer data. These conditions are consistent with larger foreshock size and reflection of solar wind protons, their most likely source. Consequently, we find that the wave occurrence rate increases with Mercury’s heliocentric distance. Detection of these waves throughout Mercury’s highly eccentric orbit suggests the conditions for backstreaming protons are potentially present for all of Mercury’s heliocentric distances, despite the relatively low solar wind Alfvén Mach number regime. These results are relevant for planetary magnetospheres throughout the solar system, and the magnetospheres of exoplanets, and provide knowledge of particle acceleration mechanisms occurring inside foreshocks.

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**Results**

**ULF Wave detection.** In this study we have analyzed all MESSENGER MAG measurements acquired upstream from Mercury’s bow shock by utilizing the maximum sampling rate of 20 vectors/s\(^3\) (see Methods, subsection The MESSENGER mission, for more details). Detection of backstreaming ion-generated ULF waves in the Hermean foreshock is based on both frequency and polarization properties\(^{30}\). We compute the Power Spectral Density (PSD) of the perpendicular and parallel components to the mean magnetic field \([\text{PSD}(B_\parallel)\text{ and PSD}(B_\perp)]\) utilizing a Fast Fourier Transform algorithm. We perform this analysis over 204.8 s intervals with upstream MAG measurements. To consider the wave polarization properties, we also apply Minimum Variance Analysis (MVA) on MAG data\(^{34}\).

Observations are analyzed in the solar foreshock coordinate system\(^{35}\). The foreshock coordinates used in this paper are \(D_{\text{IST}}\), \(\theta_{\text{BN}}\) and \(Z_0\). \(D_{\text{IST}}\) measures the distance between MESSENGER and the bow shock location along the IMF direction. \(\theta_{\text{BN}}\) is the angle between the IMF line that passes through the spacecraft location and the normal to the bow shock at the intersection point and is known to affect particle reflection [e.g.,\(^{17,18}\)]. \(Z_0\) measures the distance of MESSENGER perpendicular to the solar wind velocity- IMF \((V_{\text{SW}} - \text{B}_\text{IMF})\) plane that contains the center of Mercury. Figure 1 shows a schematic representation of the foreshock, where these variables are also presented. Hereafter, computed foreshock coordinates are the mean values over 204.8 s, over which PSD are also determined.
Spatial Distribution. We find that most of the ULF waves are observed for $\text{DIST} = [1.0 \pm 3.3] R_M$, $\theta_{BN} = [21.8 \pm 55.7] ^\circ$, and $Z_0 = [-3.4 \pm 3.4] R_M$ despite MESSENGER’s capability to detect them outside this spatial range. These results are shown in Fig. 2a-c that display the mean values of $\text{DIST}$, $\theta_{BN}$ and $Z_0$ as a function of Mercury’s heliocentric distance for all 204.8 s intervals where MESSENGER was in the Hermean foreshock (in gray) and with ULF wave detection (in pink) meeting the criteria of $r = 2$ and $\lambda_{23} = 0$. It is also worth noticing that waves appear to be present up to ~5$R_M$ both in DIST and $Z_0$, suggesting the presence of a limit from which waves are no longer present or detectable above the turbulent solar wind background. We find that such limit does not vary significantly with the explored wave selection criteria. In this study, we consider $r = 2$ and $\lambda_{23} = 0$ the minimum set of conditions to detect waves, avoiding detection of false positives. Interestingly, these quasi-monochromatic (clear dominant frequency) ULF waves are not detected above $\theta_{BN} \sim 70 ^\circ$, suggesting that backstreaming ion fluxes fall off substantially with large $\theta_{BN}$. Moreover, it is worth mentioning the presence of a minimum solar wind convection time needed for wave growth, once these fluxes are significant. This result is consistent with previous reports related to other solar system planetary foreshocks [e.g.,3,36,37].

Given the differences in MESSENGER’s foreshock sampling as a function of Mercury’s heliocentric distances (gray dots and black bars, Fig. 2), hereafter we restrict our analysis to time intervals where MESSENGER was in the spatial range where most of the waves are detected (red horizontal dashed lines, Fig. 2), regardless of the presence of waves. This allows us to determine the variability in the wave occurrence rate along Mercury’s orbit around the Sun, taking into account such spatial biases.

Conditions Favorable for ULF Waves. We find that the wave occurrence rate increases as a function of heliocentric distance (Fig. 3). This trend, observed throughout the entire MESSENGER mission, is present regardless of the explored wave selection criteria. We perform a linear fit for each of these curves, shown by the corresponding solid lines. The selection criteria and parameters associated with the best linear fits displayed in Fig. 3b are listed in Table 1. The linear correlation factors (R) and p-values suggest the correlation between the abundance of ULF waves and Mercury’s heliocentric distance is significant.

Having taken into account spatial biases due to MESSENGER’s orbit around Mercury, next we investigate the reason for the observed trends. In particular, we determine the variability of the wave’s occurrence with the IMF intensity and IMF cone angle. The latter is defined as the angle between the IMF and the solar velocity, assumed to be radial. While the IMF intensity directly affects the Alfvén Mach number, known to strongly influence the backstreaming ion fluxes (likely source of these waves), the IMF cone angle influences the plasma instability with the largest linear wave growth rate and the foreshock size.

We find a decreasing trend with more waves detected for lower values of $B = |B_{\text{IMF}}|$, for $B$ ranging between 10 nT and 50 nT, as shown in Fig. 4b. Because of its eccentric orbit and proximity to the Sun, the IMF at Mercury has a large spread of $B$ values and goes up much higher than any other planet in the solar system. By performing a polynomial fit we find that the wave occurrence rate $O(B)$ decays as $B^{-1.85}$, with a 95% confidence interval for the power law index equal to $[-2.14, -1.57]$. A decreasing trend with
a similar power law index is obtained when the other selection criteria presented in Table 1 are applied. Figure 4d also shows that these ULF waves are seen more frequently for IMF cone angles smaller than ~35° and larger than ~140°. This preferential angular range and the peaks observed for a quasi-radial IMF are observed for all explored selection criteria.

Figure 5 shows the IMF intensity and cone angle as a function of Mercury’s heliocentric distance for time intervals where MESSENGER is in the Hermean foreshock (inside the region where most of the waves were detected) and when waves are detected. Despite variability in the external conditions along Mercury’s orbit (clearly shown by the black vertical bars), we find that the preference for low $B$ and IMF cone angles is observed throughout Mercury’s heliocentric distance range. It is also worth noticing that while the background IMF intensity decreases with heliocentric distance as expected from Parker’s model, the IMF cone angle presents a slight increase with heliocentric distance but not as significant to overcome the effects that $B$ has on the wave occurrence rate.

As suggested by the results in Fig. 4, we report the presence of a clear anti-correlation between the wave occurrence rate and the IMF intensity throughout all MESSENGER mission, as can be seen from Fig. 6b, c. Such anti-correlation is the key factor responsible for the increase in the waves abundance around Mercury’s aphelion. Although waves are seen most of the time for quasi-radial IMF (Fig. 4d), the range of this angular variable is not as clearly correlated with the planet’s heliocentric distance, as shown in Figs. 5b and 6d. The best trigonometric fit in Fig. 6b is characterized by a period of ~88 days, an amplitude of 3.6% and a phase shift between Mercury’s aphelion and the local maximum.
The reader is referred to Eqs. (1–3) for a strict definition. While Eq. (4) explicitly shows a dependence on $r_{hc}$, $f(r_{hc})$ encompasses effects from hidden variables whose net effect we assume vary as $r_{hc}^n$. Therefore, Eq. (4) explicitly shows that $O$ is proportional to both $B$ and $r_{hc}$ with $\alpha$ and $\beta$ the corresponding polynomial index. Given that the IMF intensity decays with heliocentric distance as $B(r_{hc}) \sim r_{hc}^{-2}$, we also conclude that

$$O = O(r_{hc}, B) \propto B^\alpha f(r_{hc}) \propto B^\alpha r_{hc}^\beta$$  \hspace{1cm} (4)

with $-2\alpha + \beta = \gamma$. In other words, Eq. (5) shows that because of the decay of $B$ with $r_{hc}$, under these assumptions the wave occurrence rate is proportional to $r_{hc}$ to the power of $\gamma$. Moreover, the observed relationship between $O$ and $r_{hc}$, and the associated $R$ and $p$-values associated with the linear fits analogous to the ones shown in Table 1 suggest that $\gamma \sim 1$. Such linear fits are the polynomial with the smallest number of degrees of freedom that fit the observations reasonably well. However, it is important to emphasize that $\gamma \sim 1$ can be affected by the explored heliocentric distance range and the presence of hidden variables and/or temporal variability affecting the values of wave’s abundance. Despite these potential effects, we find that the wave’s occurrence rate decreases with $B$ with a power law index ranging between $-2.35$ and $-1.80$, for different fixed ranges of $r_{hc}$. This result, in addition to the observed approximate linear increasing trend with $r_{hc}$, suggest that $\beta < 0$. Interestingly, a decreasing trend between the wave occurrence rate with $r_{hc}$ for a fixed value of $B$ and IMF cone angle suggests, in turn, the presence of another variable affecting the wave abundance. A proper determination of $\alpha$ and, in particular, of $\beta$ demands additional spacecraft observations and comparison with observations at other planetary foreshock when possible.

Figure 8 presents a scheme where the wave occurrence rate increases linearly with Mercury’s heliocentric distance. At the same time, the background IMF intensity decreases, affecting the Alfvénic Mach number, a parameter known for affecting the backstreaming proton fluxes, the most likely source for the ULF waves studied in this work.
Discussion
In this work we have analyzed the dependence of the 0.05–0.41 Hz ULF wave occurrence rate on the IMF intensity and cone angle, taking into account spatial biases associated with MESSENGER trajectory. Both parameters are relevant since they affect the foreshock size, the linear wave growth rate of the plasma instabilities and the Alfvén Mach number. The latter parameter can affect the solar wind backstreaming proton fluxes responsible for the analyzed ULF waves. Waves occur preferably for quasi-radial IMF configuration, increasing the foreshock size where waves can grow. The most likely instability responsible for these waves is the ion-ion right hand resonant [e.g.,39,40]. Indeed, wave polarization and frequency range are consistent with such instability and are similar to 30-s waves previously reported at the terrestrial foreshock30. Waves also occur preferentially for relatively low IMF intensity values, that is, for relatively high Alfvén Mach numbers. Higher Alfvén Mach numbers are generally associated with increasing particle reflection at the bow shock3,21–24. In particular, Fig. 6b, c display a significant decrease in the wave occurrence rate associated with the relatively large B values, that took place around the maximum of the solar cycle 24.

Interestingly, detection of the ULF waves throughout Mercury’s orbit suggests that the conditions for backstreaming ions are potentially present for all of Mercury’s heliocentric distances.

Once excited, large-scale magnetosonic ULF waves are convected by the solar wind and transmitted through the bow shock. These waves have been detected in the downstream region of several solar system planetary magnetospheres and constitute an important source of wave energy [e.g.,41,42]. They are capable of propagating into the magnetosphere, heat the ionosphere, launch bursts of time-dispersed energetic ions and also affect escape of heavy ions from the planetary atmospheres, among other outcomes [e.g.,43–45]. Thus, we can expect significant energy transfer into the Hermean magnetosphere by ULF magnetosonic waves, despite the intrinsic properties of this planet (e.g., the lack of an ionosphere and the relatively large conductive core) and the highly variable external conditions [e.g.,46]. It is also worth mentioning that whistler waves seem to occur more frequently in the Hermean foreshock16. The determination of the physical mechanisms associated with such coupling and the relative energy contribution compared to other frequent processes in the Hermean magnetosphere, such

Fig. 4 Wave occurrence rate as a function of Interplanetary Magnetic Field (IMF) strength and cone angle. a, c Histograms of the number of selected intervals in the Hermean foreshock (gray) and with wave detection (pink) as a function of the (a) IMF intensity and (c) IMF cone angle when \( r = 2, \lambda_{23} = 0; \) b, d Associated wave occurrence rate as a function of the (b) IMF intensity (in black) and as a function of the (d) IMF cone angle. Best polynomial fit associated with wave occurrence rate as a function of IMF intensity is shown in blue (b). \( r \) is a factor associated with the intensity of magnetic field power spectral density at the wave frequency range of interest, and \( \lambda_{23} \) constitutes a threshold for the intermediate to minimum eigenvalue ratio associated with Minimum Variance Analysis. The reader is referred to Eqs. (1)–(3) for a strict definition.
and associated with the decay of the IMF intensity radially from the centric distance. Our results suggest that such variability is partly of the wave occurrence rate with the solar wind proton density and other parameters.

Finally, although the conditions (low Alfvén Mach number, low plasma beta) around Mercury are not seen very frequently around other planetary foreshocks in the solar system, this analysis allows us to identify the dependence of the wave occurrence rate on key parameters affecting the SW proton reflected fluxes in a planetary bow shock. The relationship between observed wave frequency and IMF intensity reported in and suggests that there are indeed similar acceleration mechanisms taking place in all solar system planetary foreshocks. The upstream region of interplanetary shocks constitute another plasma environment where upstream waves are observed under low Mach number regimes. In particular, ULF waves similar to the ones analyzed in the present study have been reported by and. Interestingly, the absence of steepened waveforms and shocklets upstream from low Mach number interplanetary shocks is compatible with previous analysis on the Hermean foreshock and the relatively low normalized wave amplitude and direction of wave propagation found in. Moreover, the conditions around Mercury are expected to be similar, in some respects, to the ones of several close-in exoplanets around red dwarfs, the most common type of star in the Milky Way. This is the case, for example, for several exoplanets in the TRAPPIST-1 system under conditions of minimum stellar wind total pressure. Although density and solar wind velocity regimes are clearly different, the Alfvénic Mach number is in the same order. If this is the key parameter affecting the backstreaming ions we can expect a similar process taking place around those exoplanets.

Methods
The MESSENGER mission. MESSENGER was inserted into orbit around Mercury on 18 March 2011. The spacecraft’s orbit had high eccentricity, a ~12-h period, and 82° inclination. The apogee altitude and orbital period were reduced on 16 April 2012 to ~4.1 R_M and ~8 h, respectively (R_M stands for Mercury’s radii equal to 2440 km). However, as shown in Fig. 6a, the spacecraft provided magnetic field measurements in the Hermean foreshock throughout all the mission. The reader is referred to for additional information on MESSENGER’s trajectory relative to Mercury’s magnetopause and bow shock location.

Bow shock connectivity. The methodology employed for the detection of fore-shock ULF waves is similar to the one considered in. The determination of the connection of MESSENGER to the Hermean bow shock (for each 204.8 s interval) is done based on the solar foreshock coordinates introduced by, and the average

as, magnetic reconnection, define an interesting topic for future studies.

We also report the presence of a long term trend (~1 Mercury year) where the abundance of foreshock ULF waves, likely generated by backstreaming protons, varies with Mercury’s heliocentric distance. Our results suggest that such variability is partly associated with the decay of the IMF intensity radially from the Sun. Moreover, the characterization performed by means of Eqs. (4) and (5) suggests the presence of an additional variable affecting the waves abundance. One possible candidate is the solar wind proton density. Indeed, such density decreases with heliocentric distance, thus decreasing the Alfvén Mach number for a relatively constant solar wind speed. Therefore, a linear dependence of the wave occurrence rate with n_he (as shown in Fig. 3), could be associated with a linear dependence on the Alfvénic Mach number, at least for the explored heliocentric distance range. However, it is important to emphasize that the solar wind proton density does not only affect the Alfvén Mach number. Indeed, it can also affect the linear wave growth rate and the flux of reflected solar wind protons at the Hermean bow shock. Thus, deviations from a linear dependence on the Alfvén Mach number could be present despite the results displayed in Fig. 3.

Differences in the linear fits for different wave selection criteria shown in Fig. 3b could be related to the temporal evolution of the waves. Indeed, even though the most likely source of all observed fast magnetosonic waves are backstreaming ions, the waves that present a clear peak in the PSD and a well-defined polarization state (e.g., r = 2, λ_23 = 5) are likely in an earlier evolution stage than those that only kept the peak in the PSD (e.g., r = 2, λ_23 = 0) [see, e.g., and references therein]. If this is the case, then the derived increase in the slope of the wave occurrence rate as a function of Mercury’s heliocentric distance (for a fixed r value, but for decreasing values of λ_23), can be understood in terms of the time needed to reach a given wave stage. In other words, wave events satisfying r = 2 and λ_23 = 0 (being a set of wave events that contains the previous one) is associated with both, early stage and more evolved waves. Given that the development of the latter most likely require more time with the appropriate external conditions, the fits shown in Fig. 3b suggest that the conditions favorable for these ULF waves occur more frequently as Mercury’s heliocentric distance increases. In addition, we find the wave occurrence rate decreases for increasing values of r. This can be understood in terms of the necessary energy input and the time needed to reach relatively high amplitude waves. Indeed, Fig. 3b shows a gradual decrease in the wave occurrence rate as a function of Mercury’s heliocentric distance for r ranging between 2 and 10. This could be indicative of a limit to the maximum amplitude achievable in the Hermean foreshock. BepiColombo magnetic field and particle measurements in the foreshock of Mercury are of utmost importance in order to test these conclusions and to better determine the dependence of the wave occurrence rate with the solar wind proton density and other parameters.

Fig. 5 External conditions. Interplanetary Magnetic Field (a) intensity and (b) cone angle for all intervals in the Hermean foreshock (in gray) and with wave detection (pink) as a function of Mercury’s heliocentric distance for r = 2 and λ_23 = 0, for all corresponding MESSENGER observations obtained during approximately 17 Mercury years. r is a factor associated with the intensity of magnetic field power spectral density at the wave frequency range of interest, and λ_23 constitutes a threshold for the intermediate to minimum eigenvalue ratio associated with Minimum Variance Analysis. The reader is referred to Eq. (1)-(3) for a strict definition. Black and red vertical bars span the 10th to the 90th percentiles of the gray and pink data sets, respectively, within each bin (~0.0177 AU width). The middle point in each bar corresponds to the associated median.

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bow shock fit computed in\textsuperscript{57}. For this, we perform a transformation from the aberrated Mercury solar magnetospheric (MSM) coordinates\textsuperscript{30,59} to the latter system based on\textsuperscript{35}. To determine the foreshock coordinates and bow shock connectivity associated with each interval, we compute the IMF vector and MESSENGER location in the aberrated MSM coordinate system\textsuperscript{30}. We conclude that MESSENGER was connected to the Hermean bow shock during each 204.8 s interval, if the IMF line at its mean position intersects the bow shock average fit.

Since the location of this boundary changes in response to variability in the solar wind conditions, we increase the reported estimate of the semi-latus rectum up to 30%. Taking this consideration into account, the employed methodology allows us to analyze events that took place upstream from the Hermean bow shock.

**Power spectral density and wave polarization.** Each of the analyzed 204.8 s time windows contains a minimum of ~10 wave periods (wave frequency varies with IMF intensity) and comprises 4096 magnetic field observations. The length of these intervals allows us to compute $\text{PSD}(B_{\perp})$ and $\text{PSD}(B_{\parallel})$ by means of a Fast Fourier Transform algorithm. Given that we utilize the maximum sampling rate of MAG (20 Hz), the associated spectral resolution $\Delta f$ is 0.00488 Hz. We consider a sliding window, such that the intersection between neighboring time intervals is 87.5%. Definition of $\Delta f_{\perp}$, $\Delta f_{\parallel}$ and $\Delta f_{\Delta}$ frequency intervals are based on previous reports [e.g.,\textsuperscript{11,15,16,30}] and numerical simulations\textsuperscript{60}. In particular,\textsuperscript{11} and\textsuperscript{30} have shown that the observed wave frequency of the foreshock fast magnetosonic waves under study displays a linear dependence with the IMF intensity for several solar system planetary magnetospheres. These observed wave frequencies may therefore indicate a dependence on local ion gyrofrequencies (see, for instance, Fig. 3 in\textsuperscript{30}). Our analysis is limited to cases in which the strength of the mean IMF for a given time interval is equal to or greater than 10 nT, allowing us to detect ULF waves with observed frequencies in the $\Delta f_{\Delta}$ range.

The wave polarization analysis is performed making use of the MVA technique\textsuperscript{30}. By considering sub-intervals on the order of ~4 observed wave periods (~14 s to 50 s), we are able to determine the corresponding median values and percentiles of the eigenvalues ratios, for each of the 204.8 s time interval. As shown in Eq. (3), our wave selection criteria specifically considers the 75th quartile of the $(\lambda_{2}/\lambda_{3})$ distribution.
by the presence of other wave modes, specifically when the power in one or both of these modes is on the order or larger than the waves under study. It is because of this and the size of chosen time intervals that the MVA analysis is applied up to $\lambda_3 = 5$. A similar criteria has also been used to analyze ULF waves in region upstream from the Martian bow shock\textsuperscript{45,61,62}.

Data availability

MESSENGER MAG data used in this study are publicly available through the Planetary Data System (https://pds-ppi.ippぐ.columbia.edu/search?view=flat=yes&fd=pds/PPS/MESSENGER/MAG-3-CDR-CALIBRATED-V1.0/DATA/MAG/). This data set can also be accessed following the path: /home/Mercury/Messenger/Magnetometer/MESSENGER MAG Calibrated Data Bundle/data/mso. The magnetic field data generated in this study have been deposited in https://figshare.com/s/6cb7d259ad8b01clc308. The data that support the findings of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

The code used in this analysis is based on four main routines. The Fast Fourier Transform (https://www.mathworks.com/help/matlab/ref/fft.html) and Lomb-Scargle periodogram (https://www.mathworks.com/help/signal/ref/plomb.html) developed by MATLAB, a Minimum Variance Analysis developed following\textsuperscript{34} and bow shock connectivity routine developed following\textsuperscript{18} and bow shock connectivity routine developed following\textsuperscript{13} The code is available upon reasonable request.

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The authors declare no competing interests.

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