Observations of Low-Frequency Magnetic Waves due to Newborn Interstellar Pickup Ions Using ACE, Ulysses, and Voyager Data

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Abstract. Wave excitation by newborn interstellar pickup ions (PUIs) plays a significant role in theories that attempt to describe IBEX and Voyager observations in the solar wind and heliosheath. The same dynamic processes can be far-reaching and extend into the inner heliosphere to at least 1AU and likely to smaller heliocentric distances. While the high-resolution magnetic field measurements required to study these waves are not yet available in the heliosheath, we have studied a range of available observations and found evidence of waves due to interstellar PUIs using ACE (1998–2015 at 1 AU), Ulysses (1996–2006 at 2 to 5 AU, high and low latitudes) and Voyager (1978–1979 and 2 to 6 AU) observations. Efforts to extend the Voyager observations to 35 AU are ongoing. We have examined these data sets and report on observations of low-frequency waves that result from newborn interstellar pickup $H^+$ and $He^+$ ions. Although not as common as theory originally predicted, we presently have identified 524 independent occurrences. Our conclusion from studying these waves is that they are seen only when the ambient turbulence is sufficiently weak. The instability that generates these waves requires a slow accumulation of wave energy over several to tens of hours to achieve observable wave amplitudes. In regions where the turbulence is moderate to strong,
the turbulence absorbs the wave energy before it can reach observable levels and transports the energy to the dissipation scales where it heats the background thermal particles. Only intervals with the weakest turbulence will permit energy accumulation over this time scale. These conditions are most often, but not exclusively, achieved in solar wind rarefaction regions.

1. Introduction
The solar wind (SW) and embedded heliospheric magnetic field (HMF) form a system of diverse internal dynamics. They also form a barrier to the entry of interstellar charged particles into the heliosphere. In contrast, neutral atoms enter and transit the heliosphere freely at \( \sim 23 \, \text{km}\,\text{s}^{-1} \) [1, 2, 3, 4] until they are ionized, primarily by collisional charge exchange with solar wind ions or photoionization by solar EUV flux [5, 6, 7, 8, 9, 10, 11]. Electron impact ionization may also be important for some particle species. The newly ionized atoms then become embedded in the flow as “interstellar pickup ions” (PUIs) that gyrate about the HMF at the solar wind speed at the point of ionization. As such, they constitute an energetic ion population and a source of free energy for wave excitation.

The theory of wave generation by interstellar PUIs is an outgrowth of the theory of foreshock dynamics and the theory of wave excitation at comets [12]. It predicts that waves excited by interstellar PUIs should be commonly seen throughout the heliosphere as a regular feature of the HMF spectrum. They are not. Turbulence transport theory argues that the wave energy excited by interstellar PUIs is absorbed by the turbulent energy cascade and used to heat the background plasma [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. Thermal proton temperatures are approximately constant beyond \( \sim 20 \, \text{AU} \) as a result of turbulent driving by interstellar PUIs, thereby offsetting expansive cooling. The turbulent reprocessing of the accumulating wave energy makes observations of waves due to interstellar PUIs rare and difficult to find.

In this paper we review observations of magnetic waves due to interstellar PUIs as seen by the Advanced Composition Explorer (ACE), Ulysses and Voyager spacecraft. We present their observational characteristics and the circumstances under which they are seen.

2. Observations
Because PUIs move at the solar wind speed in the plasma frame, the resonant instability produces right-hand polarized, sunward propagating fast mode waves in the plasma frame. The Doppler shift results in a spacecraft-frame wave signature that is left-hand polarized and seen at spacecraft-frame frequencies \( f_\text{sc} \geq f_{i,c} \) where \( f_{i,c} = e_i B / (m_i c^2 \pi) \) is the ion cyclotron frequency of the source ion [12]. Here \( e_i \) is the charge of the pickup ion, \( B \) is the mean magnetic field intensity, \( m_i \) is the mass of the pickup ion, and \( c \) is the speed of light. The waves at \( f_\text{sc} > f_{i,c} \) result from pitch-angle scattering of the source ion. Waves are not seen at \( f_\text{sc} < f_{i,c} \) because this would require energization of the source ion which is not generally seen outside of shocks. This gives these waves a unique signature that is distinct from many solar wind processes.

2.1. Early Ulysses Observations
The first observations of waves due to ionized hydrogen (H), pickup protons, were reported using Ulysses magnetic field data [35] recorded from early 1992 until late 1993 [36]. Thirty-one distinct intervals of waves were reported. Figure 1 reproduces one of them. Waves are seen in the power spectrum at \( f_\text{sc} > f_{p,c} \) and most of the energy lies in the components perpendicular to the mean magnetic field. Their propagation direction was unresolved due to the insufficient data rate of the thermal ion instrument and this has remained a common problem in the study of PUI waves. It was reported that the observation of the waves did not depend on the strength
Figure 1. Power spectra for first reported observations of magnetic waves due to newborn interstellar H\(^{+}\) recorded by the Ulysses spacecraft. Data interval is January 6, 1993 from 09:00 to 11:00 UT. (left to right) Spectra of the fluctuation component parallel to the mean magnetic field and two components perpendicular to the mean magnetic field. Note that the fluctuation vector is largely transverse to the mean field. Reproduced from [36].

of the magnetic field \(|B|\), but the waves were most often seen when the orientation of the field was quasi-radial.

The Ulysses spacecraft moved from 5.4 to 4.6 AU and from \(-1^\circ\) to \(-40^\circ\) heliographic latitude during the time that the events were gathered [36]. H ionization becomes most efficient at this distance from the Sun whereas inside \(\sim 4\) AU the neutral H density falls precipitously so that neutral H density at 1 AU is only \(\sim 1\%\) that of the interstellar medium [37]. The above wave observations occurred where the source was strongest.

2.2. Early Voyager Observations

While developing a turbulence data base of magnetic field spectra from the Voyager 2 spacecraft [38], a wave event was found that could be attributed to newborn interstellar PUIs [39]. The event was recorded on January 7, 1979 (Day-of-Year or DOY 7) when the spacecraft was at 4.5 AU and \(-5.4^\circ\) heliographic latitude. Unlike the previously reported Ulysses events, this interval contained waves due to both H\(^{+}\) and He\(^{+}\). Neutral He is the second most abundant interstellar atom. No shock or other likely sources of the waves were observed. The waves were observed in the middle of a seven-day rarefaction interval lasting from DOY 4 through DOY 10. There was a strong forward shock seen midway on DOY 12, but no evidence of waves between the above wave interval and the shock crossing five days later. It is unlikely that the observed waves were due to shock acceleration.

The mean field intensity was \(|B| \approx 0.5\) nT. As a result, \(f_{i, c}\) for protons was only marginally resolved by the 96 s thermal ion instrument, PLS [40], whereas \(f_{i, c}\) for He\(^{+}\) was readily observed. Cross-correlation of the magnetic and velocity fluctuations showed that the waves were Sunward propagating as expected.

Realizing that low-frequency waves due to interstellar PUIs had been found in rarefaction regions, a second survey of Voyager 1 and 2 observations from DOY 329 of 1977 through DOY 288 of 1979 (2 to 6.2 AU) was undertaken [42]. Figure 2 shows three examples of spectra computed, but not shown, as part of that study. The left stack shows an example of waves due to newborn interstellar pickup He\(^{+}\). Note the abrupt rise in the power at the He\(^{+}\) cyclotron frequency \(f_{He, c}\), along with the moderate rise in the degree of polarization and coherence and the fact that the same frequencies are left-hand circularly polarized in the spacecraft frame as shown by the ellipticity. The middle panel shows typical solar wind spectra without observable waves. It is
Figure 2. Our analysis of three intervals of Voyager 2 magnetic field data with times marked at the top of each stack. Each stack contains (top to bottom) the spectrum of the total power and power in $|B|$, degree of polarization, coherence, ellipticity, angle between the minimum variance direction and the mean magnetic field, and the normalized magnetic helicity. The left stack shows our analysis of a time when waves due to newborn interstellar pickup $\text{He}^+$ are present. The middle stack shows our analysis of a control interval without evidence of waves due to PUIs. The right stack shows our analysis of a time when waves due to newborn interstellar pickup $\text{H}^+$ are present.

a broken power law without significant spectral features at either $f_{\text{He,c}}$ or $f_{\text{p,c}}$. The right stack shows an example of waves due to newborn interstellar $\text{H}^+$. There is an abrupt rise in the power spectrum at $f_{\text{p,c}}$ and a moderate enhancement in the degree of polarization and coherence. The ellipticity $\simeq -1$, which extends back to $f_{\text{He,c}}$, suggests that newborn $\text{He}^+$ may also be involved, but not enough to significantly alter the power spectrum. The magnetic helicity agrees closely with the ellipticity.

Eleven events were found using data from both Voyager 1 and 2 magnetic field data [42] including the event previously studied [39]. Ten events showed waves due to $\text{He}^+$, seven showed waves due to $\text{H}^+$, and six showed signatures of both sources. One event that showed a power spectral feature indicative of a $\text{H}^+$ source was right-hand polarized in the spacecraft frame. In all other regards, the observation appears to be excited by newborn interstellar pickup $\text{H}^+$. There is presently no good explanation for the observed polarization.

2.3. Later Ulysses Observations

Since the observations were proving to be scarce and there are no reliable large-scale signatures of likely wave intervals, unlike foreshock dynamics which are readily found by the presence of shocks, a better search method was needed. A spectrogram code was written for the Ulysses magnetic field data to provide continuous output of spectra including polarization parameters.
Data from 1996 through 1999 and 2003 through 2006 was analyzed [43, 44, 45, 46]. The gap from 2000 through 2002 represents the fast latitude scan and was omitted from this study. A total of 502 wave intervals were uncovered with all but two seen beyond 4 AU. Those two seen inside 4 AU were beyond 3.5 AU. There was a discernable peak in the observation rate at 5 AU once the distribution of heliocentric distances across the spacecraft trajectory was taken into account. Wave events tend to last less than 5 hrs in the spacecraft data. This is not a measure of their lifetime in the plasma, but rather a measure of the spatial extent of the waves. The waves are seen in \( \sim 3.6\% \) of the data. Quasi-radial mean magnetic fields are favored, but not required. A strong solar cycle dependence is not seen.

The observed wave events consistently demonstrated high degrees of polarization and coherence at the relevant frequencies. They had minimum variance directions that were quasi-parallel to the mean magnetic field. Most observations were left-hand polarized in the spacecraft frame, but \( \sim 10\% \) were right-hand polarized.

![Figure 3](image.png)

**Figure 3.** Daily spectrogram of ACE magnetic field data for DOY 184 of 1999. Top to bottom, the panels are the total magnetic field intensity \(|B|\) and radial component \(B_R\); power spectrum; percent polarization; ellipticity; angle between the minimum variance direction and the mean magnetic field; and the coherence. The spacecraft-frame gyrofrequencies of \(\text{H}^+\), \(\text{He}^+\), and \(\text{O}^+\) are indicated in the spectrograms by the blue, red, and magenta traces, respectively. Note the blue patch around noon in the ellipticity at frequencies \(f_{\text{He,c}} < f_{\text{sc}} < f_{\text{p,c}}\). These fluctuations are highly coherent and strongly polarized with nearly circular polarization. These are left-hand polarized waves in the spacecraft frame that arise from newborn interstellar pickup \(\text{He}^+\). The right-hand polarized fluctuations at higher frequencies have not been studied.
2.4. ACE Observations

Taking a lesson from the Ulysses analysis, a daily spectrogram code was written for the ACE magnetic field data [47, 48]. Figure 3 shows one such daily spectrogram that contains waves due to pickup He$^+$. Those spectrograms are now available to anyone at the ACE Science Center [49] as a routine data product and are very useful in preliminary examinations for a range of investigations at kinetic physics scales. Eighteen years of data were surveyed from launch in late 1997 into 2015. Twenty-five wave events were found to result from newborn interstellar He$^+$ [50, 51]. We did not investigate the ACE data for waves due to pickup H$^+$ since the density of interstellar H is very low at 1 AU and it is difficult to discount foreshock sources in this case.

Data rates for the thermal ion instrument on ACE preclude cross-field correlation in an effort to determine wave propagation directions at this time scale [52]. All twenty-five wave events show high degrees of polarization and coherence with minimum variance directions there were quasi-parallel to the mean magnetic field. All but two of the wave events were left-hand polarized in the spacecraft frame. This has become a recurring theme in this analysis. Approximately 10% of all waves seen in association with interstellar pickup ion sources have the “wrong” polarization. This is true for both H$^+$ and He$^+$ sources.

Each December, ACE passes through the He focusing cone [53], a region with $\sim 3 \times$ the normal density of interstellar neutral He and as a result, we expect to see a higher abundance of wave events during this period. However, waves are seen throughout the year and at any time in the solar cycle. The relative strength of the wave source does not seem to provide the sole explanation for when waves are seen. This appears to be true for Ulysses and Voyager observations as well.

3. Observability

In our more extensive survey efforts [42, 46, 51] we also analyzed an approximately equal number of control intervals selected from times near the wave intervals when the ambient conditions appeared similar but no waves were observed. The Ulysses wave events were shown to exist when the background power spectrum is lower than in control intervals [46]. However, this effect alone could not explain absence of the intense wave features which were originally predicted [12]. Our studies have indicated the importance of an additional process.

We take the expression for the time-asymptotic wave power spectrum [12]:

$$I_{\pm}(k, \infty) = \frac{1}{2} \left\{ |C(k)|^2 + 4I_+(k,0)I_-(k,0) \right\}^{1/2} \pm \frac{1}{2} C(k)$$

(1)

where

$$C(k) = I_+(k,0) - I_-(k,0)$$

$$+ \ 2\pi NV_A m_i |\Omega_{i,c}| k^{-2} \left[ \Omega_{i,c} k^{-1} v_0^{-1} - \left( \Omega_{i,c} k^{-1} v_0^{-1} - \mu_0 \right) |\Omega_{i,c} k^{-1} v_0^{-1} - \mu_0 |^{-1} \right]$$

(2)

and $I_+(k,0)$ ($I_-(k,0)$) is the background spectrum for the anti-sunward (sunward) propagating fluctuations at wavenumber $k$. All $k$ are assumed to be parallel to the mean magnetic field. For sunward propagating waves, the wave vectors $k < 0$ ($k > 0$) denote the right-hand polarized fast-mode (left-hand polarized Alfvén) waves. Here $m_i$ is ion mass, $N_i$ is the PUI number density, $\Omega_{i,c} = e_i B / (m_i c)$ is the ion cyclotron frequency $= 2\pi f_{i,c}$, $V_A$ is the Alfvén speed, $v_0$ is the PUI speed in the plasma frame $\approx V_{SW}$ where $V_{SW}$ is the solar wind speed and $\mu_0$ is the pitch angle of the newborn ions.

The time required to scatter the PUI is on the order of an hour and the time required to accumulate the observed wave energy is on the order of 20 hrs. This suggests that the PUI distribution remains a scattered distribution throughout the wave energy accumulation process.
Figure 4. Scatter plot for wave growth rate $dE_W/dt$ vs. turbulent transport rate $\epsilon$ for the Ulysses wave observations (red triangles) and control intervals (black circles). The diagonal line is unity. Wave observations favor growth rates that are greater than turbulence rates. Control intervals where waves are not seen favor turbulence rates that are greater than wave growth rates. Reproduced from [46].

ACE and Voyager observations show similar results for both $\text{He}^+$ and $\text{H}^+$ pickup ions [42, 51]. Therefore, we do not use linear theory based on the initial PUI ring distribution to compute the rate of wave energy excitation over the lifetime of the observation. For our purposes we will take the derivative of eq. 1–2 holding all background variables constant so that the accumulation rate, $dE_W/dt$ is controlled by the PUI production rate, $dN_i/dt$.

We can also compute the rate at which the wave energy is transported through the inertial range via turbulent cascade (according to MHD extensions of the Kolmogorov theory [54, 55, 56]):

$$\epsilon = \frac{f^{5/2}[E(f)]^{3/2} \cdot 21.8^3}{V_{SW} N_P^{3/2}}$$

where $E(f)$ is the measured magnetic field power spectral density in units of nT$^2$Hz$^{-1}$, which is assumed to vary as $f^{-5/3}$. Equipartition of magnetic and kinetic energy is assumed, $R_A = 1$. $N_P$ and 21.8$^3$ are part of the conversion of the magnetic field to Alfvén units. This choice is based on the assumption that the turbulent cascade of the background fluctuations is essentially two-dimensional and this controls the rate at which the wave energy is absorbed by the turbulent cascade. Eq. 3 disagrees with that used by [55] by a factor of $2\pi [(5/3)(1 + R_A)/C_K]^{3/2} \sim 6\pi$ where the Komogorov constant $C_K = 1.6$ [57], but this expression is more nearly in agreement with the observed heating rates at 1 AU [56].

Figure 4 shows a scatter plot for the computed wave excitation and turbulent cascade rates for wave events and control intervals used in the Ulysses analysis [46]. The dashed line is unity. Although not perfect, wave events tend to show wave growth rates in excess of the turbulent cascade rates while the control intervals show computed turbulence rates that exceed the wave growth rates. Thus we find that the waves are seen when the background turbulence is sufficiently weak to allow the wave energy to accumulate to observable levels, thereby explaining why these waves are so rarely observed. Similar results are found for ACE [51] and Voyager [42] observations and for waves due to $\text{He}^+$ and $\text{H}^+$ PUIs.

4. Later Voyager Analyses

We have modified the daily spectrogram code used in the ACE analysis to plot Voyager magnetic field data and applied the code to the data currently available in the National Space Science Data Center (NSSDC). The data extends from launch in September 1977 through 1990 and includes data resolution 1.92 s, 9.6 s and 48 s. We have scanned the data, found $\sim 400$ wave events, and are in the process of analyzing the results.
Figure 5. (top) Daily data coverage of Voyager 1 2 s magnetic field data. Note abrupt decline in coverage beginning 1981. (bottom) Times of waves due to newborn interstellar ions (either H$^+$ or He$^+$ or both) currently under study. Approximately 200 intervals showing waves due to PUls are currently known. The Voyager 2 data set shows $\sim 3 \times$ as many wave intervals in the same time interval.

Figure 5 shows the daily coverage of Voyager 1 magnetic field 1.92 s data (top) and the times when waves due to pickup ions are seen (bottom). This list continues to be refined. An incomplete search of the Voyager 2 data set reveals $\sim 3 \times$ as many wave events for the same years. Wave observations extend out to include observations in 1990 when Voyager 1 was at $\sim 40$ AU and Voyager 2 was at $\sim 35$ AU. We find waves due to He$^+$ and H$^+$ source ions that include the most distant observations. Reduced data coverage starting in 1981 and the shorter data intervals due to reduced spacecraft tracking work in tandem with the reduced $|B|$ and $f_{i,c}$ to make resolution of the waves increasingly difficult as the spacecraft move to greater heliocentric distances. This reduces our ability to study the waves at the greater heliocentric distances, but they are still found.

5. Bernstein Waves

Although distinct from the above observations, an additional wave event was discovered in the Voyager 2 magnetic field data [41]. This event was measured on DOY 350 of 1978, 199 days before the Jovian encounter. Strong aliasing in the 1.92 s data suggested a signal at greater than the Nyquist frequency and so the highest resolution (0.32 s) MAG data was obtained to study this event. The waves were seen to evolve from $\sim 0.18$ Hz to $\sim 0.67$ Hz in the spacecraft frame with the magnetic fluctuations transverse to the mean magnetic field. The magnetic field intensity was $|B| \simeq 0.3 \text{nT}$ and perpendicular to the radial (solar wind flow) direction. The solar wind speed was a nominal 423 km s$^{-1}$. The thermal proton density and temperature were unusually low at 0.07 cm$^{-3}$ and 0.57 eV, respectively. A careful analysis ruled out the likelihood of whistler waves and it was concluded that these signals were Bernstein waves. Gyrating newborn interstellar PUls were inferred to be the source of the waves. No other such event has since been found in the Voyager data.
6. Discussion and Summary

The papers we have reviewed here present many additional features of the waves due to newborn interstellar pickup ions. They show the frequency of occurrence, duration of wave events in the data set, relative rate of observation according to solar cycle and season, the properties of the waves, and how those properties sometimes differ from current theoretical predictions, and the time required to reach the observed wave energy levels. In the process, we have demonstrated the utility of computing automated daily spectrograms in an effort to aid in the search for candidate events.

We have used a prediction for the turbulent cascade that derives from the Kolmogorov theory for hydrodynamics. Other theories exist [13, 58, 60, 61, 62, 63, 64, 65, 66]. Third-moment expressions for the turbulent cascade suggest a high degree of variability between similar samples that lies outside what was considered here [67, 68], although the long growth time also suggests that the wave growth persists over a sufficiently extended period of time to allow the local cascade rate to vary significantly and possibly average to what the steady-state theories suggest.

In many applications of plasma instabilities that operate in the solar wind at kinetic scales, such as in planetary, interplanetary and cometary foreshocks, wave excitation and particle scattering are rapid processes due in large part to the greater density of energetic particles. Little to no concern is given to whether the background turbulence can act to limit wave growth. However, the long wave growth times associated with interstellar PUIs provide an exception to the rule. This does not mean that waves are not excited when they are not observed. Every indication from theory and observations suggests that the wave excitation process is ongoing at all times. When the turbulence is too strong to permit the waves to grow to observable levels, the wave energy is still being absorbed by the turbulence and used to heat the background ions. Only the ability to accumulate wave energy to observable levels is absent.

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