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ACE observations of magnetic waves arising from newborn interstellar pickup helium ions

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Key Points:

- Discovery of waves due to interstellar pickup He^+
- Such waves can be found at 1 AU
- The observations match theoretical predictions

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Abstract We report low-frequency magnetic waves that were observed by the Advanced Composition Explorer (ACE) spacecraft on day of year 180 of 1999 with characteristics consistent with the predictions of waves excited by newborn interstellar pickup He^+ ions. This event was found by examining daily spectrograms of MAG data, a new data product that is now available to the community via the ACE Science Center. The event shown here is one of approximately 20 similar events that will be analyzed in future studies. This event is fairly typical of those we have found so far. The waves exist at spacecraft-frame frequencies between the He^+ cyclotron frequency and approximately twice the H^+ cyclotron frequency. Fluctuations are transverse to the mean magnetic field, are noncompressive, circularly polarized, have field-aligned minimum variance directions, and are left-hand polarized in the spacecraft frame as predicted by theory. The event lasts for just under 1 h.

1. Introduction

Here we present an analysis of one interval of ACE/MAG data that is consistent with waves excited by newborn, interstellar pickup He^+ ions. It is typical of ~20 such events we have found. An extensive review of the properties of interstellar pickup ions can be found in *Zank* [1999]. Their basic properties were originally predicted by *Blum and Fahr* [1970], *Axford* [1972], *Holzer* [1972], and *Vasyliunas and Siscoe* [1976], but the ions were not observed until later [*Möbius et al.*, 1985; *Gloeckler et al.*, 1993; *Geiss et al.*, 1994; *Drews et al.*, 2013, 2015]. Interstellar pickup ions originate as neutral atoms that enter the heliosphere at a relatively slow speed (~ 23 km s^{-1} relative to the Sun) [*Möbius et al.*, 2012; *Bzowski et al.*, 2012] and are eventually ionized. Neutral H is the most abundant interstellar atom and is ionized through charge exchange with solar wind thermal ions and photoionization by solar UV. The ionization of H is strongest within ~10 AU of the Sun, resulting in an ionization cavity with an exponential reduction of interstellar H atoms inside ~ 4 AU. As a result, interstellar pickup H^+ ions are not expected to be seen at 1AU. Interstellar He atoms are ionized primarily by photoionization by solar UV and do reach inside 1AU. Neutral He atoms which flow past the Sun are gravitationally focused into a cone of elevated density downstream. The Earth passes through the inner regions of this focusing cone late every year, although newborn He^+ ions are present at 1AU at all heliolongitudes.

Wave excitation by newborn interstellar pickup ions and the resulting self-consistent ion scattering has been described by *Wu and Davidson* [1972], *Lee and Ip* [1987], and *Isenberg* [1996]. The neutral atoms possess very little velocity relative to the Sun, so newborn interstellar ions are taken to move at the solar wind speed in the solar wind frame of reference. Their initial pitch angle and guiding center motion depends on the orientation of the mean magnetic field at the ionization site. As they stream sunward in the solar wind, they resonate with ambient waves propagating in the same direction with plasma-frame polarizations (right-hand polarization) and wavelengths matching the particle motion in the solar wind frame. As a result, the newly interacting ions generate characteristic waves which appear in the Doppler-shifted spacecraft frame at, and above, the cyclotron frequency of the particle species. These waves are generated primarily with sunward propagation parallel to the mean magnetic field with wave speeds near the Alfvén speed. Above the cyclotron frequency, the power spectrum is predicted to fall as f^{-2} where f is the wave frequency in the spacecraft frame [*Lee and Ip*, 1987]. Since the solar wind speed exceeds the Alfvén speed, the Doppler-shifted polarization in the spacecraft frame is opposite of that in the plasma frame, and the waves are measured as left-hand polarized.

Murphy et al. [1995] first reported 31 examples of waves due to interstellar H^+ as seen by the Ulysses spacecraft. The development of spectrograms made finding these waves significantly easier. A database of 502 such observations in the Ulysses data was developed from the spectrogram observations and subsequently analyzed [*Smith et al.*, 2010; *Cannon et al.*, 2013, 2014a, 2014b]. *Joyce et al.* [2010] reported one observation of He^+-excited waves in the Voyager data set at 4.5AU. Although both H^+- and He^+-excited waves are predicted to be ubiquitous [*Lee and Ip*, 1987], they are actually relatively rare. *Cannon et al.* [2014b] argued that the ambient solar wind turbulence is too strong to allow for the gradual accumulation of wave energy in all but the most extreme intervals of weak turbulence. These conditions are most commonly found in solar wind rarefaction regions.

We have found ~ 20 intervals of likely wave activity arising from newborn interstellar He^+. Here we show our analysis of one such event.

2. Data Analysis

We use data from the magnetic field instrument [*Smith et al.*, 1998] aboard the ACE spacecraft [*Stone et al.*, 1998; *Garrard et al.*, 1998] to compute mean field directions and spectra of the fluctuations. Data from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) instrument on the ACE spacecraft [*McComas et al.*, 1998a] provides context for the analysis.

2.1. Spectrograms

Daily spectrograms of the magnetic field observations represent a new data product that has been released by the ACE/MAG team and made available to the community at the ACE Data Center web site (http://www.srl.caltech.edu/ACE/ASC/). Examination of these daily spectrograms is the means by which we found the wave event shown here. Daily spectrograms are made using full resolution 3 vector/s MAG data. Standard FFT techniques are employed. Short data gaps are interpolated, with larger gaps resulting in the loss of spectral information for that time interval.

Power and polarization spectra are computed in the usual manner. The real part of the diagonal elements of the covariance matrix contains the power spectrum for each component. The imaginary part of the covariance matrix of the magnetic field contains information only about circularly polarized signals [*Means*, 1972]. From this, we can determine the components of the minimum variance direction, **k**, and transform into the wave normal system. In this system, the plane wave power is contained in the transverse plane, allowing us to separate the unpolarized and polarized components [*Fowler et al.*, 1967; *Rankin and Kurtz*, 1970]. Wave polarization properties are then obtained in terms of the components of the covariance matrix.

Figure 1 shows the daily spectrogram for day of year (DOY) 180 of 1999. Horizontal lines in all but the Figure 1 (first panel) denote the cyclotron frequency, $f_{i,c} = eB/(2\pi m_i c)$, for singly charged H (blue), He (peach), and Oxygen (pink). From Figure 1 (first panel) to Figure 1 (sixth panel) are as follows: Total field strength $|\mathbf{B}|$ (black) and the radial component B_R (blue), trace of the power spectral matrix (total power in the fluctuations), percent polarization (often called degree of polarization) of the fluctuations bound between 0 and 1, ellipticity (positive for right-handed waves in spacecraft frame) bound between −1 and 1, angle between the minimum variance direction **k** and the mean magnetic field **B**, $cos^{-1}(\mathbf{k}\cdot\mathbf{B})$, bound between 0° and 90°, and the coherence of the fluctuations bound between 0 and 1.

Similar to the pickup H^+ observations of *Cannon et al.* [2014a], the waves are not easily seen in the spectrogram of the power. The waves are much more readily seen in the polarization spectra early in the day from approximately 180.04 to 180.08 (180::00:57 to 180::01:55UT). This is particularly true of the ellipticity spectrum where we see a bright blue patch at frequencies greater than the He^+ cyclotron frequency, $f > f_{\mathrm{He},c}$, indicating these fluctuations are left-hand polarized. Likewise, there is a strong signal in the percent polarization and coherence. While less evident, these same frequencies are seen to have $\mathbf{k} \parallel \mathbf{B}$. At this time, the field is largely radial forming a 10° angle with the radial direction.

There also exist other interesting features in this same day starting approximately midday. There is a multi-hour interval of right-hand polarized waves at frequencies greater than the H^+ cyclotron frequency, $f >> f_{p,c}$, around noon and shorter intervals of left-hand polarized waves at similar frequencies later in the day. These are likely related to dissipation processes and are not the subject of this paper.

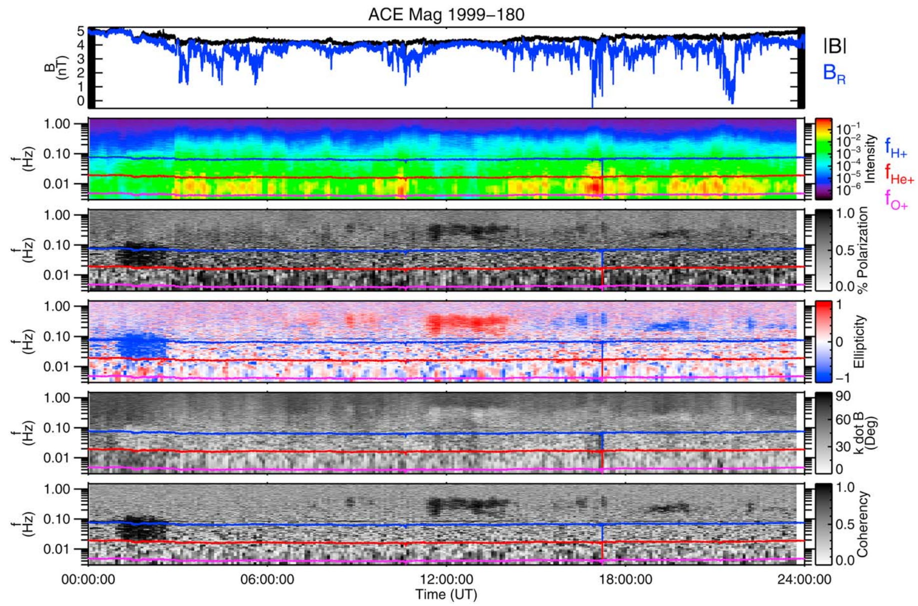

Figure 1. Magnetic spectrogram for DOY 180 of 1999. (first panel) Magnetic field intensity, $|\mathbf{B}|$, (black) and radial component, B_R, (blue); (second panel) power spectrum; (third panel) percent polarization $0 \le D_{\mathrm{pol}} \le 1$; (third panel) ellipticity $-1 \le E_{lip} \le 1$; (fifth panel) angle between the minimum variance direction and the local mean magnetic field $0 \le \Theta_{kB} \equiv cos^{-1}(\mathbf{k} \cdot \mathbf{B}) \le 1$; and (sixth panel) coherence $0 \le C_{\mathrm{oh}} \le 1$.

2.2. Rarefaction

Figure 2 shows the solar wind conditions for a 7 day period surrounding the observations. The Figure 2 (top) shows the solar wind speed, V_{SW}, and the Figure 2 (bottom) shows the proton density, N_P, as reported by the SWEPAM instrument. The wave event at the start of DOY 180 is in the middle of a prolonged rarefaction interval where the wind speed falls from ∼900 km s^{-1} early on DOY 179 to ∼500 km s^{-1} near the start of DOY 181. The average wind speed during the wave event is 579kms^{-1}. As a result, the density has fallen to 0.7 p$^+$ cm^{-3}, the average magnetic field is $|\mathbf{B}| = 4.7$ nT and almost radially aligned with $\Theta_{BR} = 9.6°$, and the Alfvén speed is elevated to 123 km s^{-1}. Past studies [*Joyce et al.*, 2010; *Cannon et al.*, 2014a, 2014b] have suggested that waves due to newborn interstellar pickup ions are most readily found in rarefaction regions and in other situations where the background turbulence is low.

There is an oblique shock 3 days after the wave event at the start of DOY 183 with a shock normal angle Θ_{Bn} ∼69°and an Alfvén Mach number M_A ∼1.8. The observed wave event is too far upstream to be associated with the shock, and there is no evidence of upstream waves between the wave event described here and the shock. The nearest shock before the event is on DOY 178. There is no evidence of an interplanetary source for the waves observed in Figure 1. In the section 3 we do consider the possibility that the waves are due to energetic protons coming from the Earth's bow shock.

This paper attributes the waves to resonance with newborn interstellar pickup He$^+$. The SWEPAM instrument has measured He$^+$ of solar origin [*McComas et al.*, 1998b; *Skoug et al.*, 1999] but is not sufficiently sensitive to

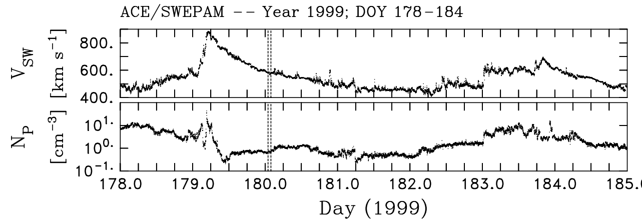

Figure 2. (top) Solar wind speed and (bottom) proton density as measured by the ACE/SWEPAM instrument during the period surrounding the wave event. The wave event occurs midway through the rarefaction interval and is marked by two vertical dashed lines at the beginning and the end of the interval.

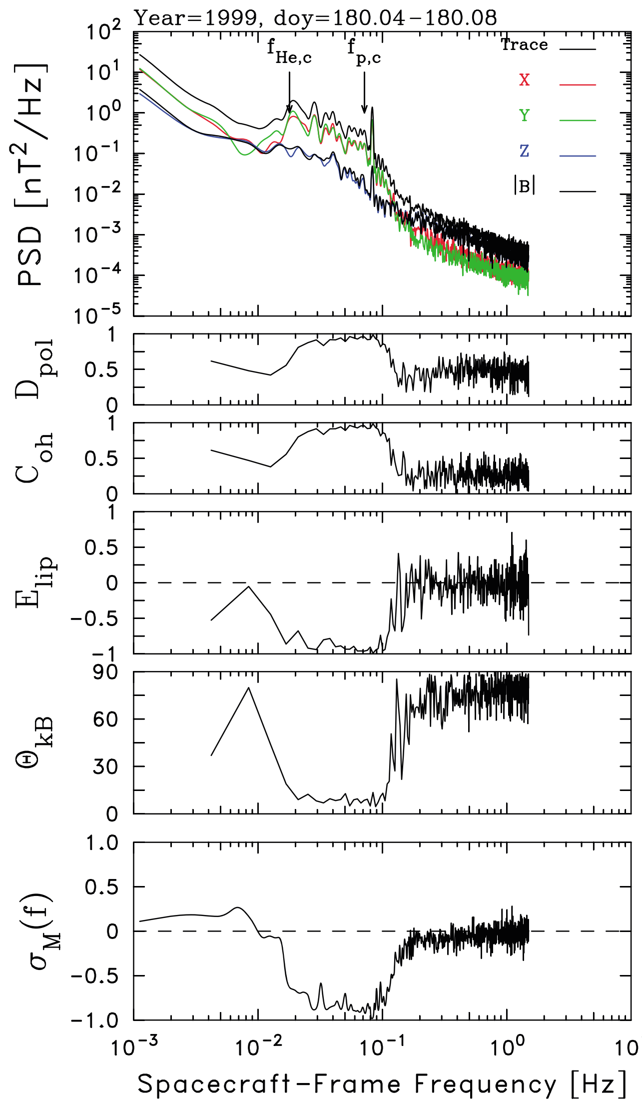

Figure 3. Analysis of magnetic field data for DOY 180.04–180.08. (first panel) Total power spectrum (upper black curve), transverse components (red and green), parallel component (blue), and spectrum of |**B**| (see text for definitions of components); (second panel) degree of polarization; (third panel) coherence; (fourth panel) ellipticity; (fifth panel) angle between the minimum variance direction and the mean magnetic field; and (sixth panel) normalized magnetic helicity.

record the low densities associated with the interstellar source. The Solar Wind Ion Composition Spectrometer (SWICS) instrument does measure interstellar pickup He^+ [*Gloeckler et al.*, 1998] and finds no discernable increase in intensity at this time (Jason Gilbert, private communication, 2015).

2.3. Detailed Spectra

After finding the wave events via the spectrograms, we proceed to analyze the observations using carefully constructed subsets of the data that attempt to capture the wave event. Figure 3 shows the results of our analysis of the wave event shown in Figure 1. The specific time interval is DOY 180.04 to 180.08 in 1999. Figure 3 (first panel) to Figure 3 (sixth panel) are as follows: the power spectra for the three components of the magnetic field rotated into mean field coordinates plus the trace and spectrum of |**B**|; the degree of polarization, D_{pol}; the coherence, C_{oh}; the ellipticity, E_{lip}; the angle between the minimum variance direction and the mean field, $\Theta_{kB} \equiv \cos^{-1}(\mathbf{k} \cdot \mathbf{B})$; and the normalized magnetic helicity, σ_M [*Smith*, 1981; *Matthaeus and Smith*, 1981; *Matthaeus and Goldstein*, 1982; *Matthaeus et al.*, 1982]. The power and magnetic helicity spectra were computed via Blackman-Tukey spectral techniques, while the polarization spectra were computed via FFT of the time series [*Mish et al.*, 1982]. FFT methods were also used to compute the power and helicity spectra, were found to agree with the spectra shown, and are not shown here. The power and polarization spectra are computed in mean field coordinates [*Belcher and Davis*, 1971; *Bieber et al.*, 1996], while the helicity is computed in standard heliographic coordinates of necessity.

Both $f_{p,c}$ and $f_{\mathrm{He},c}$ are shown in Figure 3 (first panel). The power spectra are shown in mean-field coordinates prescribed by ($e_B \times (e_R \times e_B)$, $e_R \times e_B$, e_B) where e_R and e_B are the unit vectors in the radial and magnetic field direction, respectively [*Belcher and Davis*, 1971; *Bieber et al.*, 1996]. The two components of the magnetic field perpendicular to the mean field are shown in Figure 3 (first panel) (red and green, respectively). The power spectrum of the field-aligned component is shown in blue. The upper black curve is the trace (total power), and the lower black curve is the power in $|\mathbf{B}|$. The wave power is strongly enhanced at $f > f_{\mathrm{He},c}$. The bulk of the power in the wave enhancement at $f > f_{\mathrm{He},c}$ resides in the perpendicular components meaning that the fluctuations are largely transverse to the mean magnetic field. The two perpendicular components contain nearly identical energy at these frequencies which is indicative of circular polarization. The trace spectrum behaves as f^{-2} at frequencies $f_{\mathrm{He},c} < f < f_{p,c}$ as predicted [*Lee and Ip*, 1987] but begins to fall more steeply at $f > f_{p,c}$ possibly due to incomplete pitch-angle scattering of the newborn He^+ at the time of observation.

The degree of polarization and the coherence are both high (near the maximum value 1) in this same frequency range. At greater and lesser frequencies the value of both is small. The ellipticity approaches -1 indicating left-hand circularly polarized fluctuations consistent with waves excited by a beam of newborn interstellar ions moving sunward and parallel to the mean magnetic field. At greater and lesser frequencies $E_{lip} \simeq 0$. The angle $\Theta_{kB} \simeq 0$ in this frequency range suggests wave propagation parallel to the mean magnetic field. At greater and lesser frequencies Θ_{kB} approaches 90°. Last, the normalized magnetic helicity approaches -1 and is consistent with the measured ellipticity. At greater and lesser frequencies $\sigma_M \simeq 0$.

This analysis is incapable of distinguishing between parallel propagation in the sunward and antisunward directions. The ACE/SWEPAM instrument is not fast enough to resolve ion distribution moments at these frequencies and does not provide the necessary solar wind velocity fluctuations needed to discern the propagation direction of these waves.

3. Discussion

Although wave excitation by newborn interstellar H^+ is highly unlikely at 1AU and would not be seen at frequencies as low as the He^+ cyclotron frequency, it is necessary to consider the possibility that the waves reported here may have something to do with the Earth and its foreshock. The dominant accelerated foreshock ion is H^+ followed by He^{2+}. Little or no significant He^+ levels have been reported upstream of Earth. H^+ ions can only produce waves at these low frequencies if the ion energy is 16× the minimum energy required to move upstream of the shock. ACE is $\sim 235 R_E$ upstream of the Earth where H^+ intensities are down almost 3 orders of magnitude relative to the wave-generating intensities at the shock [*Lee*, 1982]. However, H^+-generated waves are seen at L_1 and cannot be ruled out entirely.

Likewise, it seems unlikely that these observations are related to the Low Frequency Wave, LFW storm, observations of *Jian et al.* [2010, 2014]. Those observations tend to be seen at higher frequencies $f \geq f_{p,c}$ and with mixed polarization. *Jian et al.* [2014] argues credibly that LFM storm events are not related to newborn insterstellar or cometary pickup ions.

One of the difficulties in assessing the source of these observations is that the interstellar pickup ion source provides a very weak instability with a slow accumulation of wave energy. The source ions are argued to be omnipresent with the observation of the waves controlled by the changing ambient turbulence level [*Cannon et al.*, 2014b]. It is therefore difficult to correlate the observation with an evolving source as is so often the case for observations of kinetic instabilities. The fact that the wave frequencies and polarization so accurately match the predicted forms for waves due to newborn interstellar pickup He^+ makes this the most likely interpretation.

4. Summary

We have reported one observation of waves due to newborn interstellar He^+ by the ACE spacecraft. The waves match the expected characteristics: they are seen at frequencies in excess of the He^+ cyclotron frequency with fluctuations perpendicular to the mean magnetic field and minimum variance directions along the field. The spacecraft-frame polarization is left-hand circularly polarized as expected. The event is seen when the mean field is 10° from the radial direction. Although not shown here, we have reproduced the analysis of

Cannon et al. [2014b] which shows that the growth rate for pickup-ion-generated waves exceeds the turbulent cascade rate at this time, thereby allowing the wave energy to accumulate.

While it is impossible to rule out the possibility that ions accelerated at the Earth's bow shock are involved in the production of these waves, the data most nearly fits the interstellar pickup ion predictions. At the present time $\sim$ 20 such events have been found and are now the subject of further study.

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