Large-amplitude, Wideband, Doppler-shifted, Ion Acoustic Waves Observed on the Parker Solar Probe

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Abstract

Electric field spectra measured on the Parker Solar Probe typically contain upwards of 1000 large-amplitude (∼15 mV m⁻¹), wideband (∼100–15,000 Hz), few-second-duration, electric field waveforms per day. The satellite also collected about 85 three-second bursts of electric field waveforms per day at a data rate of ∼150,000 samples per second. Eight such bursts caught these waves, all of which were located in switchbacks of the magnetic field. A wave burst on 2019 September 7, when the spacecraft was at an altitude of ∼55 solar radii, is described. It contained Doppler-shifted ion acoustic waves that propagated in the direction opposite to the local magnetic field at all rest-frame frequencies from 60 Hz to nearly the proton plasma frequency of 2200 Hz, while no other wave modes were present. The eight bursts all contained ion acoustic waves whose individual net potentials were ≤1 V. A second burst, analyzed in conjunction with ion plasma measurements, showed that the ion acoustic waves were associated with broadened, plateaued, ion spectra containing unheated ions. Because the ion acoustic waves had phase velocities that varied from 140 to 90 km s⁻¹, ions interacting with these waves via the Landau resonance had a chance to diffuse in parallel velocity space from 90 to 140 km s⁻¹ in the plasma rest frame. The most likely generation mechanism of the ion acoustic waves is the ion–ion acoustic instability, while the electron–ion instability is a less likely candidate.

1. Introduction

Spectral measurements aboard the Helios I and II spacecraft, at radial distances from 0.3 to 1 au, demonstrated an abundance of broadband electrostatic fluctuations at frequencies below the local electron plasma frequency (Gurnett & Anderson 1977; Gurnett & Frank 1978). The typical electric field strength of these broadband fluctuations was 1 mV m⁻¹ at 0.3 au and it decreased approximately as 1/R with increasing radial distance, R, from the Sun. The electric field strength was positively correlated with the electron to ion temperature ratio, $T_e/T_i$, as well as with the electron heat flux (see the review by Gurnett 1991). The high-resolution spectral measurements aboard the Voyager spacecraft showed that broadband spectra of the electrostatic fluctuations measured aboard Helios were actually due to highly intermittent electrostatic fluctuations, with the central frequency changing on timescales of less than a second (Kurth et al. 1979). Early Helios and Voyager spacecraft measurements allowed interpretation of the broadband electrostatic fluctuations in terms of ion acoustic waves that were Doppler-shifted and measured at relatively high frequencies (up to the electron plasma frequency) in the spacecraft rest frame, due to their short wavelengths, which scaled with the local Debye length. The instabilities potentially producing the broadband electrostatic fluctuations include the ion beam instability (also known as the ion–ion-acoustic instability; Lemons et al. 1979; Gary & Omidi 1987) and electrostatic electron heat flux (electron–ion) instability (Forslund 1970), but no consensus was reached on the origin of these waves in the solar wind (Gurnett 1991).

There is a consensus that solar wind heating occurs due to the dissipation of magnetic field turbulence and coherent electromagnetic fluctuations that are naturally produced in the expanding solar wind plasma (e.g., Cranmer et al. 2009; Alexandrova et al. 2013; Gary 2015; Matthaeus et al. 2015). The microscopic processes that convert the magnetic field energy into heat are not entirely established though. A substantial part of the turbulence dissipation can occur at electron scales due to the damping of various electrostatic fluctuations produced by kinetic instabilities of unstable electron and ion distribution functions naturally formed in the course of development of the magnetic field turbulence cascade (e.g., Alexandrova et al. 2013; Bruno & Carbone 2013). In particular, ion acoustic waves in the solar wind can be generated by ion beams that are produced by low-frequency turbulent magnetic field fluctuations (Valentini & Velti 2009; Valentini et al. 2011, 2014). In this scenario, ion acoustic waves provide thermalization of the ion beams, resulting in ion heating and termination of the turbulence cascade at short scales.

Until recently, in situ observations of the broadband electrostatic fluctuations in the solar wind were restricted to spectral measurements at radial distances larger than 0.3 au. The recently launched Parker Solar Probe mission provides measurements of both spectra and electric field waveforms in the region closer to the Sun than any earlier mission (Fox et al. 2016). In this paper, we demonstrate that these broadband electrostatic fluctuations in the frequency range from ∼100 Hz to tens of kHz are commonly present in the inner heliosphere, that these fluctuations are linearly polarized, electrostatic, ion acoustic waves with their $k$-vector antiparallel to the local background magnetic field, and that they have amplitudes up to
above a few hundred hertz are associated with rapid changes of the polarity of the frequencies from 10 Hz to 100 kHz.

Figure 1. Electric and magnetic field measurements from 17:00 to 18:00 UT on 2019 September 7. (a), (b) Spectra of AC- and DC- coupled electric fields covering frequencies from 10 Hz to 100 kHz. (c) The magnetic field in SC coordinates with the z-axis pointing sunward. The bursts of the electric field power spectral density above a few hundred hertz are associated with rapid changes of the polarity of the $B_z$ magnetic field component associated with switchbacks.

~15 mV m$^{-1}$. We use ion measurements to argue that these ion acoustic waves are produced by ion beam instabilities.

2. Data

The Parker Solar Probe satellite is in a solar orbit with a perihelion that is lowered by interactions with Venus on occasional orbits. The electric field experiment on this satellite consists of four cylindrical booms in the spacecraft $X$–$Y$ plane, which is perpendicular to the satellite–Sun line near perihelion (Bale et al. 2016, 2019). The geometric half-length of each antenna pair is 3.5 m, which is somewhat larger than the spacecraft dimensions and is the order of the local Debye length. Electric field measurements are successfully made with this boom system, in spite of the small size of their antennas, because they are current-biased and because of the high-level symmetry between the probes, sunlight, and the generally radial magnetic field and solar wind flow (Bowen et al. 2020; Mozer et al. 2020a).

Data from the electric field experiment is transmitted at various rates. The data rate of interest in the present work is ~150,000 samples per second, which provides waveform data covering the frequency range from 100–50,000 Hz (Malaspina et al. 2016). About 85 such bursts were collected per day near perihelion, with each burst lasting about 3.5 s. In addition, nearly continuous electric field spectra over the frequency range from 10 Hz to 5 kHz are available at a 6 s cadence as are electric field spectra over the frequency range from 5–100 kHz at 0.1 s cadence (Bale et al. 2016).

3. Ion Acoustic Wave Observations

Figure 1 presents an overview of electric field spectra and the background magnetic field measured during 17:00–18:00 UT on 2019 September 7. Figures 1(a) and (b) present power spectral densities of the AC- and DC-coupled electric fields. The spectra demonstrate that there are bursts of electric field power spectral density over a broad frequency range from a few hundred hertz to several kilohertz (the electron gyrofrequency was about 800 Hz and the proton plasma frequency was 2200 Hz). Note that some bursts were seen in one of the burst panels but not the other. This is due to the different time resolutions of the measurements in the two panels and may result from the increased sensitivity of the higher resolution channel to dust impacts and/or time domain structures (Mozer et al. 2020a). Nevertheless, careful inspection of the data shows that there were about 45 bursts of interest in this typical one-hour interval. Figure 1(c) shows that the occurrence of these bursts is tightly correlated with changes in polarity of the magnetic field component $B_z$ in switchbacks, which are magnetic field structures quite typical of the inner heliosphere (Dudok de Wit et al. 2020; Krasnoselskikh et al. 2020; Mozer et al. 2020b; Tenerani et al. 2020). In contrast to the previous measurements, the instruments aboard Parker Solar Probe allow analysis of the waveform in the broadband electric field fluctuations. As will be shown, these waves are electrostatic because the $k$-vector is antiparallel to the background magnetic field.

Figure 2 presents data from one such burst that occurred at 17:49:52 UT on 2019 September 7. Figure 2(a) shows that the magnetic field had a small $Z$-component, such that the magnetic field was largely in the $X$–$Y$ plane of the electric field measurement. Figure 2(b) presents the two measured components of the electric field, which show that the event lasted about 1 s and had an amplitude of 10 mV m$^{-1}$.

To find the wave modes in this burst, it is necessary to know the phase relationship between the EX and EY components. This is plotted in the phase relationship plot of Figure 2(c), which shows that the two components were in phase at all times and all frequencies during the event. Thus, the electric field was linearly (not circularly) polarized and whistlers were not present in spite of the fact that waves at frequencies less than the electron gyrofrequency (800 Hz) were observed. Figure 2(d) shows that the waves extended in frequency from ~100 Hz to about 5000 Hz in the spacecraft frame.

In order to further identify the wave mode, it is necessary to know the phase relationship between the magnetic and electric fields. This is possible because, during the event of interest, the
background magnetic field was largely in the $X$–$Y$ plane of the electric field measurement. To study the phase relationship, the field data in the $X$–$Y$ plane were rotated, at each time step, into a frame having $B_Y' = 0$. Figure 3(a) gives the magnetic field in this prime frame in which, because $B_Z$ was small, the magnetic field was almost entirely in the $X$-direction. Figure 3(b) gives the electric field in this prime frame, which is also nearly completely in the $X$-direction. The waves at 12 local peaks in the power spectrum are plotted in the prime frame in Figures 4 and 5. As expected, at all frequencies from 100–3700 Hz, the wave electric fields were in the same direction as the background magnetic field, and thus the waves must have been electrostatic.

The only electrostatic plasma mode at the observed frequencies is the ion acoustic mode, whose frequency in the plasma rest frame is given by the dispersion relation:

$$\omega_{\text{pl}} = k \cdot c_s / (1 + k^2 \lambda^2)^{1/2},$$

where $\omega_{\text{pl}} = 2\pi \nu_{\text{pl}}$ is the angular wave frequency in the plasma rest frame, $k$ is the wavenumber, $c_s = (T_e/m_e)^{1/2}$ is the ion sound speed (142 km s$^{-1}$), and $\lambda$ is the local Debye length (9 m).

(The density and temperature used to estimate the above values came from the SPAN instrument; see Whittlesey et al. 2020.)

The observed waves are Doppler-shifted from their frequency in the plasma rest frame due to the spacecraft motion with respect to the plasma, as described by the following expression:

$$\omega_{\text{sc}} = \omega_{\text{pl}} + k \cdot v_{\text{sw}} \cdot \cos(k \cdot v_{\text{sw}}),$$

where $\omega_{\text{sc}} = 2\pi \nu_{\text{sc}}$ is the angular wave frequency in the spacecraft frame, $\nu_{\text{sc}}$ is the wave frequency in the spacecraft
frame, $v_{sw}$ is the solar wind speed ($240 \text{ km s}^{-1}$), and $\cos (\mathbf{k} \cdot \mathbf{v}_{sw})$ is the cosine of the angle between the $k$-vector and $\mathbf{v}_{sw}$.

Because the wave may propagate parallel or antiparallel to the magnetic field, there are two possible values for $\cos (\mathbf{k} \cdot \mathbf{v}_{sw})$, either $+0.4$ or $-0.4$. Therefore, the frequencies were computed for both cases as

$$\nu_{sc}^{(+)} = \nu_{pi} k \lambda (1 + k^2 \lambda^2)^{1/2} + 0.4 \mathbf{k} \cdot \mathbf{v}_{sw} / 2\pi,$$

$$\nu_{sc}^{(-)} = \nu_{pi} k \lambda (1 + k^2 \lambda^2)^{1/2} - 0.4 \mathbf{k} \cdot \mathbf{v}_{sw} / 2\pi,$$

where $\nu_{pi}$ is the ion plasma frequency of 2.2 kHz. We note that both $\nu_{sc}^{(+)}$ and $\nu_{sc}^{(-)}$ are positive, because the frequency measured in the spacecraft frame is an unsigned quantity. The result of computations of $\nu_{sc}^{(+)}$ and $\nu_{sc}^{(-)}$ versus $k \lambda$ are presented in the left plot of Figure 6 in which the $y$-axis gives either $\nu_{sc}^{(+)}$, $\nu_{sc}^{(-)}$, or $\nu_{pl}$ (the wave frequency in the plasma rest frame), depending on the color of the plot. The dots give the measured and derived frequencies. For $k \lambda < 2$ the branch $\nu_{sc}^{(-)}$ (waves propagating antiparallel to the plasma flow and parallel to the magnetic field) does not contain frequencies as great as those measured in the spacecraft frame, so it is not an allowed solution. We stress that at $k \lambda \gg 1$ the measured frequencies could be explained with this assumption, but that regime is physically impossible because, at $k \lambda \gg 1$, the ion acoustic waves are strongly damped due to Landau resonance with thermal ions (e.g., Gurnett 1991). On the contrary, the branch $\nu_{sc}^{(+)}$ (waves propagating parallel to the plasma flow and antiparallel to the magnetic field) explains the measured frequencies of the ion acoustic waves well.

The table in Figure 6 tabulates the measured wave frequencies of Figures 4 and 5 as well as their frequencies, wavelengths, and phase velocities in the plasma rest frame. The measured frequencies span a range from well below to well above the electron gyrofrequency, and the wavelengths span the range from 5–230 Debye lengths. Because of the $(1 + k^2 \lambda^2)^{1/2}$ term in Equation (1), the ion acoustic wave is dispersive. This effect is evidenced by the variation of $\nu_{pl} / k$ in the last column of the table. This dispersion of the ion acoustic waves may be important for facilitating ion thermalization by these waves.

The specific feature of the event in Figures 1–2 is that the magnetic field was almost in the $XY$ plane and, hence, the actual electric field of the ion acoustic waves could be measured. However, there were no simultaneous ion measurements for that event to address the generation mechanism of these waves. Therefore, a second burst event illustrated in Figure 7 was studied in order to determine the relationship between ion fluxes and ion acoustic waves. The phase plot of Figure 7 shows that EX and EY in this event were 180° out of phase, which means that the electric field component in the $X-Y$ plane was linearly polarized. Figure 7(b) shows that the power in the wave extended from low frequencies to

Figure 4. Examples of different wave-component frequencies in the prime coordinate system of Figure 3. Because EX' is much greater than EY', the electric field was parallel to the background magnetic field at all displayed frequencies.
Figure 5. Further examples of higher frequency components of the wave burst showing, again, that the electric field at all frequencies was parallel to the background magnetic field.

Figure 6. Analysis of Doppler-shifted frequencies, $\nu$, of ion acoustic waves in the spacecraft frame. In the left panel, the frequency in the plasma rest frame is given by the black curve, while the red and blue curves represent frequencies in the spacecraft frame for waves propagating antiparallel and parallel to the magnetic field. The table in this figure summarizes, in respective columns, the observed wave frequencies, the wave frequencies in the plasma rest frame, the wavelengths, and the phase velocities of the waves.

**Electron gyrofrequency = 800 Hz**

**Debye length = 9 meters**
Figure 7. Parameters of a second wave burst showing the waveform (c) in the prime frame having $BY' = 0$ (d). The $180^\circ$ phase difference between EX and EY (a) shows it was linearly polarized and its bandwidth (b) extended to about 15 kHz.

Figure 8. The wave burst of Figure 7 seen in a larger context. The burst (b) occurred during the fourth of seven ion acoustic wave events whose spectra are illustrated in (a). In the first half of this figure, the ions fluxes at three energies ((c), (d), and (e)) were more or less constant, while they increased and varied during the ion acoustic events in (a). These increases occurred without ion temperature changes (f) and while the magnetic field was stable and unchanging (g).
15,000 Hz. The electric field waveform of Figure 7(c) is illustrated in a prime coordinate system which is rotated in the $X-Y$ plane such that the magnetic field in this prime plane is in the $X'$ direction (see Figure 7(d)). Because the electric field of Figure 7(c) is also in this direction, the wave is a Doppler-shifted ion acoustic wave. We note that the measurements in the $XY$ plane provide only a part of the electric field of the ion acoustic waves. In fact, in the prime coordinate system the magnetic field $B_i$ and $B_z$ components are comparable and, hence, the actual electric field of the ion acoustic waves is oriented at about 45° to the $XY$ plane and is actually a factor of 1.5 times larger than measured by the Parker Solar Probe. We conclude that the actual electric field amplitude of the ion acoustic waves in this event is up to 15 mV m$^{-1}$.

This burst event is displayed in Figure 8(b) during a 15 s interval. In Figure 8(a), the electric field spectra show that there were no ion acoustic wave events during the first 8 s of the plot and there were seven such events toward the end of the plot. The fourth of these events is the one for which the burst waveform of Figure 8(b) was collected. It is interesting that this was the lowest amplitude, narrowest bandwidth event of the seven. Figures 8(c)–(e) give the ion energy flux at three energies which are below the peak of the distribution (Figure 8(c)), at the peak (Figure 8(d)), and above the peak (Figure 8(e); Whittlesey et al. 2020). At each of these energies, the fluxes were approximately constant during the first 8 s when there were no ion acoustic wave events, and they all varied (increased) during the wave events. In spite of these flux variations, the ion temperature of Figure 8(f) did not change. These variations were not likely to have resulted from changes of detector fields of view because the magnetic field of Figure 8(g) remained roughly constant during the 15 s interval.

Thus, Figure 8 supports a correlation between ion acoustic waves and ion fluxes.

The spectral broadening of Figure 8 is seen on a shorter timescale in Figure 9, which shows nine ion spectra obtained during the 7 s interval of ion acoustic waves illustrated in Figure 7. That the correlation between waves and ions existed on an even finer timescale is illustrated by Figure 7(e), in which the ion flux at 230 eV was correlated with the ion acoustic waves of Figure 7(c) to within about 1 s. Figure 9 also shows that the ion distribution plateaued at times during this 7 s interval.

4. Discussion

Continuous spectral measurements on the Parker Solar Probe show that there were upwards of 1000 large-amplitude, wide bandwidth, few-second-duration waveforms observed per day. They are identified as outward moving, Doppler-shifted, ion acoustic waves from the fact that their $k$-vector is antiparallel to the background magnetic field, as is shown in events when the magnetic and electric field were both in the $X-Y$ plane. Among the ~85 transmitted wave burst intervals on the day of interest, there were 20 bursts that had significant electric fields (the remainder contained either dust or noise). Eight of these 20 bursts were collected inside switchbacks and all eight were found to be ion acoustic waves. Thus, it appears that broadband ion acoustic waves are a general feature of switchbacks that occur frequently near the Sun.

These ion acoustic waves occur in coincidence with broadening and plateauing of the ion distribution function but without apparent ion heating. They are dispersive, with their phase velocity changing by about 30% from their lowest rest-frame frequency of 60 Hz to about 1700 Hz. Knowledge of their wavelengths allows estimating their net potentials. In
particular, in the first event, ion acoustic waves with frequencies of 300–400 Hz had amplitudes of 2–4 mV m$^{-1}$ and wavelengths of 500–700 m, which imply that the electrostatic potentials were 3 mV m$^{-1}$, 600 m$^{-2}$ $\pi \sim 0.3$ V. The waves at other frequencies have similar amplitudes. Thus, the broadband electrostatic bursts consisted of small-potential waves at various frequencies. Because the ion acoustic waves had phase velocities that varied from 140 to 90 km s$^{-1}$, ions interacting with these ion acoustic waves via the Landau resonance have a chance to diffuse in parallel velocity space from 90 to 140 km s$^{-1}$ in the plasma rest frame.

There are two types of instabilities capable of producing the measured ion acoustic waves. First, the ion acoustic waves may result from a current-driven or heat flux instability (e.g., Forslund 1970; Lemons et al. 1979). The threshold for this instability is rather high at values of $T_e/T_i$ typical of the solar wind. For this instability at $T_e/T_i$ of the order of 1, the drift velocity of electrons with respect to ions should be about the electron thermal velocity. In this scenario, ion acoustic waves are driven due to the Landau resonance with a small fraction of resonant electrons. Because of the rather high electron drift velocity threshold at $T_e/T_i \sim 1$, this instability is highly unlikely to operate in the presented events as well as in the solar wind in general. The second possible instability is the ion–ion-acoustic instability (Lemons et al. 1979; Gary & Omidi 1987). In this instability, the ion acoustic waves are produced by resonant ions due to the presence of two ion populations that are streaming with respect to each other. This instability is most likely to produce the waves measured in the solar wind because, as has been shown, there is a plateau in the measured ion distribution function at the times of the waves, indicating a relaxed distribution in the presence of an ion beam. The evidence for the ion–ion instability is the correlation between the flux of ions and occurrence of the waves. Because there is a general (but not one-to-one) correlation between the ion acoustic waves and the low-frequency magnetic turbulence inside switchbacks, it is plausible that the wave energy comes from these low-frequency magnetic field fluctuations, which may produce ion beams, according to recent numerical simulations (Valentini et al. 2011, 2014).

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