Different Types of Ion Populations Upstream of the 2013 October 8 Interplanetary Shock

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Abstract

We show for the first time that different types of suprathermal ion distributions may exist upstream of a single interplanetary shock. ACE and the two ARTEMIS satellites observed a shock on 2013 October 8. The ARTEMIS P1 and P2 spacecraft first observed field-aligned ions (P1) and gyrating ions (P2) arriving from the shock. These were followed by intermediate ions and later by a diffuse population. At the location of the P2 the shock exhibited an Alfvénic Mach number of \( M_A = 5.7 \) and was marginally quasi-perpendicular (\( \theta_{\text{IMF}} = 47^\circ \)). At P1 spacecraft the shock was weaker (\( M_A = 4.9 \)) and more perpendicular (\( \theta_{\text{IMF}} = 61^\circ \)). Consequently, the observed suprathermal ion and ultra-low-frequency wave properties were somewhat different. At P2 the ultra-low-frequency waves are more intense and extend farther upstream from the shock. The energies of field-aligned and gyrating ions in the shock rest-frame were \(~20\) keV, which is much more than in the case of the stronger (\( M_A = 6–7 \)) Earth’s bow shock, where they are less than 10 keV.

Key words: acceleration of particles – interplanetary medium – plasmas – shock waves – solar wind – waves

1. Introduction

High-energy particles, such as solar energetic particles (SEPs; e.g., Reames et al. 1996; Schwenn 2006) and energetic storm particles (e.g., Cohen 2006), are common in the solar system. It is important to study them since they present a hazard for spacecraft, humans in space, and even our ground-based technologies such as power grids. The SEPs are also interesting since they can be used to study the elemental and isotopic composition of the Sun and particle acceleration mechanisms (Williams et al. 1998).

Significant accelerators of energetic particles in the solar system are collisionless shocks that belong to two major groups: planetary and interplanetary (IP) shocks. Planetary shocks form when the solar wind (SW) encounters obstacles such as planets with intrinsic magnetospheres (e.g., Mercury, Earth, Saturn, Jupiter; see, for example, Bagenal 1992; Russell 1993), planets with induced magnetospheres such as Venus and Mars (e.g., Luhmann et al. 2004), and active comets (e.g., Cravens & Gombosi 2004). Due to their form, planetary shocks are also called bow shocks. The major drivers of the IP shocks are interplanetary coronal mass ejections (ICMEs; Sheeley et al. 1985) and stream interaction regions (SIRs; Gosling & Pizzo 1999). In particular, the ICME-driven IP shocks have been recognized as important accelerators of energetic particles (e.g., Kahler 2003; Manchester et al. 2005).

When the fast magnetosonic Mach number \( M_{ms} \) of a collisionless shock exceeds a certain critical value \( M_c \), the shock is called supercritical. The \( M_c \) depends on several parameters, such as the angle between the direction of the upstream interplanetary magnetic field (IMF) and the shock normal, \( \theta_{\text{IMF}} \) (Edmiston & Kennel 1986). The supercritical shocks dissipate the kinetic energy of the incoming SW by energizing and reflecting a portion of the incident particles (ions, electrons) back upstream. Shocks are further divided according to \( \theta_{\text{IMF}} \). For \( \theta_{\text{IMF}} < 45^\circ \) (≥45°), they are called quasi-parallel (quasi-perpendicular). In the case of the Earth’s bow shock, the reflected ions have been observed for \( \theta_{\text{IMF}} < 70^\circ \) (e.g., Eastwood et al. 2005). These are also called backstreaming particles. Interaction of backstreaming ions with the incident SW ions results in the growth of ultra-low-frequency (ULF) waves (e.g., Dorfman et al. 2017). At Earth these waves have periods of \(~30\) s on average. The region upstream of quasi-parallel shocks populated with ULF waves (suprathermal ions) is called the ULF-wave (suprathermal ion) foreshock (e.g., Eastwood et al. 2005 and references therein).

In the case of Earth, there are plenty of observations of backstreaming particles. Near the leading edge of its foreshock a spacecraft first observes field-aligned ion beams (FABs; Gosling et al. 1978; Thomsen 1985; Kis et al. 2007; Meziane et al. 2013). These ions stream upstream along the IMF and exhibit highly collimated, beam-like distributions in velocity space. Their energies are below 10 keV, and they are not accompanied by ULF waves although they are responsible for their generation (Thomsen 1985; Eastwood et al. 2005). The FABs are also considered to be the seeds of the so-called diffuse ions (e.g., Fuselier et al. 1986; Kis et al. 2004), which show almost isotropic distributions in the SW frame with a small average bulk velocity directed sunward. These ions are observed upstream of the almost parallel section of the Earth’s bow shock; they exhibit energies up to several hundreds of keV and are accompanied by compressive ULF fluctuations. The third kind of suprathermal ions is called intermediate (Paschmann et al. 1979) with distributions intermediate between the FABs and diffuse ions. They are thought to form because farther from the edge of the foreshock the ULF waves disrupt the FAB ions, scattering them in pitch angle (PA), which leads to crescent-shaped and later to diffuse distributions. Other ion distributions have also been observed: Paschmann et al. (1982) observed the so-called gyrating ions that exhibit distribution peaks at non-zero PAs relative to the IMF. Special cases of gyrating distributions are gyrotropic ions with distribution being a torus with a symmetry axis parallel to the IMF direction (Winske et al. 1984) and gyrophase-bunched ions (Gurgiolo et al. 1981, 1983; Eastman et al. 1982; Thomsen 1985).
In order to distinguish between the FABs and the gyrating ions, we use criteria similar to Savoini et al. (2013 and references therein). Backstreaming ions are classified as FABs if they exhibit pitch angles between $\sim 0^\circ$ and $\sim 30^\circ$, while they are denominated as gyrating ions if their pitch angles extend to larger values (e.g., $\sim 90^\circ$).

Although ions in suprathermal particle energy range have been observed upstream of IP shocks at 1 au, they mostly exhibit diffuse distributions (e.g., Armstrong et al. 1970; Gosling 1983; Gosling et al. 1984; Bavassano-Cattaneo et al. 1986). It is not clear whether these ions were actually accelerated by IP shocks near 1 au or whether they are just low-energy parts of SEPs.

Only two works report observations of ion populations other than diffuse upstream of IP shocks: Viñas et al. (1984) show ion spectra upstream of an IP shock observed on 1978 February 3 obtained by the Voyager 1 Faraday cups; however, no distributions were obtained. Tokar et al. (2000) reported observations of suprathermal FAB upstream of an IP shock observed by the ACE mission (Stone et al. 1998) on 1998 April 7, but the authors could not determine details of the ion distribution functions.

Gosling (1983) stated that we should not expect to observe non-diffuse ion distributions upstream of IP shocks. The IP shocks have large curvature radii (of the order of 0.5 au at a heliocentric distance of 1 au compared to a few tens of Earth radii, $R_E$, of the Earth’s bow shock), which means that the magnetic field lines stay connected to them for very long times, typically for a day or longer. At planetary shocks these times are of the order of 10 minutes. In the case of the planetary shocks, we can observe the process of particle acceleration from the beginning, when B-field lines first connect to the bow shock. In the case of IP shocks, we expect to observe acceleration processes at later stages, hence we would detect diffuse ions. Another problem is that spacecraft are usually not equipped to measure ion distributions continuously from SW thermal to suprathermal energies.

Here, we present the first observations of different types of suprathermal ion distributions upstream of a single IP shock that was observed on 2013 October 8, by ACE and the ARTEMIS P1 and P2 spacecraft. We combine the cross-calibrated measurements of the ARTEMIS thermal and energetic particle sensors, obtaining 3D ion distributions covering the key suprathermal energy range. The P1 and P2 spacecraft first observed field-aligned and gyrating ions arriving from the IP shock. As the shock approached, the ion distributions changed to intermediate and then to almost diffuse. These observations confirm that the same ion acceleration mechanisms that are at work at Earth’s bow shock also act at IP shocks. However, in the case of the latter, the ions can be accelerated to higher energies compared to those at Earth’s bow shock.

2. Data Sets

We use measurements of the two identical ARTEMIS spacecraft orbiting the Moon (Angelopoulos 2011). Magnetic field measurements are provided by the Fluxgate Magnetometer (FGM; Auster et al. 2008). The FGM data are only available in spin (4 s) cadence. Plasma measurements are provided by the Electrostatic Analyzer (ESA; McFadden et al. 2008) and Solid State Telescope (SST; Angelopoulos et al. 2008). ESA provides ion measurements between $\sim 5$ eV and $\sim 25$ keV. SST provides ion data between 25 keV and 6 MeV.

During the time of interest ESA and SST switched from the Fast Survey Mode to the Slow Survey Mode, which affects the cadence of the omni-directional ion spectra and of three-dimensional ion distributions. A detailed description of the ESA and SST operational modes and the explanation on how the combined spectra and distributions from both instrument were obtained, are available in Appendix B.

We also use the ACE magnetic field data from the MAG instrument (Smith et al. 1998) with a 1 s cadence.

All the spacecraft coordinates and measured vectors are given in Geocentric Solar Ecliptic (GSE) coordinate system, which is defined so that the X-axis points from the Earth toward the Sun and the Z-axis toward the ecliptic north pole. The Y-axis completes the right-hand system.

3. Observations

We selected the 2013 October 8 IP shock from the Catalog of IP shocks observed in the Earth’s neighborhood by multiple spacecraft between 2011 and 2014 available at http://usuarios.geofisica.unam.mx/primo2/IPS_shocks.html. ACE observed the shock at 19:40:49 UT, while the ARTEMIS P1 and P2 spacecraft observed it at 20:16:56 UT and 20:16:24 UT, respectively. At the times of the shock passage the three spacecraft were located at (247.0, −25.0, 0.9) $R_E$, (56.5, 20.6, −4.6) $R_E$, and (56.2, 25.7, −4.6) $R_E$ (Figure 1).

The separations of the ARTEMIS spacecraft from the Moon were 10.2 and 2.6 lunar radii ($R_L$) along the Sun–Moon line and 2.0 $R_L$ and 10.7 $R_L$ perpendicular to it for P1 and P2, respectively. According to Harada et al. (2015), these distances are large enough so that no significant Moon-related ion fluxes should be detected by either of the ARTEMIS spacecraft. Also, the IMF orientation indicates that the spacecraft were not magnetically connected to the Moon nor to the Earth’s bow shock (Figure 1).

The shock normal and the $\theta_{bz}$ at each spacecraft were calculated using the magnetic coplanarity method (e.g., Schwartz 1998): ($−0.02$, 0.96, $−0.27$) and 74$^\circ$ at ACE, ($−0.81$, 0.1, 0.58) and 61$^\circ$ at P1, and ($−0.8$, 0.13, 0.59) and 47$^\circ$ at P2 (other methods, such as mixed methods (Schwartz 1998) provided very similar results). The $\theta_{bz}$ values at P1 and P2 do not overlap regardless of the method used. The estimated shock speeds in the spacecraft frame and the Alfvénic Mach numbers $M_A$ were calculated to be 428 km s$^{-1}$ and 4.9 at P1 and 456 km s$^{-1}$ and 5.7 at P2. The $\theta_{bz}$ was smaller at P2, where the $M_A$ was higher. While the shock normal directions are similar at P1 and P2, at ACE the normal differs by 90$^\circ$. This is not surprising since it was shown by Szabo (2005) that the IP shock normals may differ greatly when the spacecraft separations perpendicular to the Sun–Earth line are of several tens of $R_E$.

3.1. Reflected Ions

The 2013 October 8 shock was driven by a complex event composed of an SIR and at least one ICME. Figure 2 shows ARTEMIS P1 (panels (a)–(c)) and P2 (panels (d)–(f)) observations from 19:10 UT to 20:30 UT. The panels (a) and (d) exhibit combined SST and ESA ion spectra (the colors represent the logarithm of the particle energy flux), panels (b) and (e) exhibit IMF components, and panels (c) and (f) show...
the SW velocity components. The red vertical lines and roman numerals show times of the distributions exhibited in Figure 3.

Figure 3 shows particle (ion) distribution functions (PDF) at five different times obtained by P1 (panels (i)–(v)) and P2 (panels (vi)–(x)) spacecraft. In both cases, there are four PDFs observed upstream and one downstream of the shock. Note that the ion spectra in Figure 2 and PDFs in Figure 3 were made with different data sets resulting in some discrepancies between the two figures (see Appendix C).

In Figures 2 (a) and (d), we can see a red trace centered at ∼470 eV, which is the SW. It corresponds to the red circular spot on all panels in Figure 3. The FABs are barely detected by ESA, but they appear as a light-blue trace at ≲200 keV in the SST part of the spectra.

In all panels of Figure 3, part of the ion PDF around the SW core is missing. This occurs when the intensity of suprathermal ions is less than the sensitivity of the instrument. Figure 5 in Appendix D illustrates this by showing the signal from both instruments and their corresponding one-count levels. For ESA, the intensity of the reflected suprathermal ions was mostly below the one-count level, except during the last ∼15 minutes before the shock crossing. In contrast, the lowest energy channels of SST are much more sensitive and can detect these suprathermal ions.

We first look at the P1 distributions and ion spectra. Figure 3(i) shows the first particle distribution function featuring FABs during the time interval centered at 19:15:06 UT. The FABs appear as a blue and purple traces with velocities at $V_\parallel \sim 2000$ km s$^{-1}$ and $V_\perp$ between −600 and 100 km s$^{-1}$. These velocities correspond to energies of ∼21 keV in the spacecraft frame. We also calculate suprathermal ion kinetic energies in the shock rest-frame by subtracting the shock velocity with respect to the spacecraft (428 km s$^{-1}$ along the shock normal), but the result remains roughly the same. Such kinetic energies of the FABs are much higher than in the case of the Earth’s bow shock, where the FABs exhibit energies less than 10 keV (Thomsen 1985). It seems that although the IP shock studied here had a lower $M_A$ than the typical Earth’s bow shock near its subsolar point, the IP shock is able to accelerate the FABs to much higher energies. This is probably related to the IP shock’s large curvature radii and long connection times of the IMF field lines to the shock. Ions that reflect at the quasi-perpendicular section of the IP shock remain at such sections for longer periods and, consequently, the shock drift and shock surfing acceleration mechanisms act for longer periods accelerating ions to higher energies.

The flux of the reflected ions in Figure 2(a) intensifies with time, and their maximum energy increases and eventually reaches ∼200 keV. Figure 3(ii) shows the PDF at 19:21:55 UT. We can see that the ion beam has broadened. The peak of the distribution lies along the magnetic field, but the beam extends to the upper right quadrant. The maximum velocities of the ions are ∼6000 km s$^{-1}$ in the spacecraft frame, corresponding to energies of ∼190 keV. Just before the shock (panel (iv)) the ion PDF becomes diffuse, as revealed by the SST measurements.
Downstream of the shock (panel (v)) the ions are heated and their distributions become isotropic.

In the case of the \( P_2 \) spacecraft, the observed PDFs look a bit different. First, we note an intense spot in the lower right quadrant in panels (vi)–(viii) marked by a crossed purple ellipse. A careful inspection of the PDFs in the \( X_{\text{GSE}}-Y_{\text{GSE}} \) plane revealed that this signal comes from the direction of the Moon. It is not related to any ions but it is caused by the reflected photons coming from the Moon, so we will disregard it. We still see ions in the upper right quadrant in panel (vi). These are non-gyrotropic ions. At later times (panels (vii) and (viii)) we observe intermediate ion PDFs and just before the shock arrival (panel (ix)) the ion PDF is almost completely diffuse. Again, downstream of the shock we observe an isotropic, heated ion PDF (panel (x)).

### 3.2. Upstream Waves

Figure 4 shows \( B \) magnitude (black) and \( -B_x_{\text{GSE}} \) component (blue) in panels (i) and (iv) (corresponding to \( P_1 \) and \( P_2 \) observations, respectively). Panels (ii) and (v) show wavelet spectra of the \( B \) magnitude, while panels (iii) and (vi) show the spectra for the \( B_x_{\text{GSE}} \) component. The shaded intervals correspond to times when the upstream ULF waves are present. The waves appear \( \sim 7.8 \) minutes before the shock arrival in the case of \( P_2 \) and \( \sim 5.2 \) minutes before in the case of \( P_1 \). At first they are highly transverse, but they become more...
compressive closer to the shock front. Their frequencies are between 0.02 and 0.1 Hz (periods between 10 and 50 s). By comparing Figures 2 and 4 we can see that the FABs coincide with times when no ULF waves are present, but that the almost diffuse ion PDFs appear together with upstream ULF waves that exhibit an important compressive component.

4. Discussion and Conclusions

We report the first observations of different suprathermal ion distributions upstream of the single 2013 October 8 IP shock. These observations were made with the two ARTEMIS spacecraft. The shock properties, the ion PDFs and the upstream ULF-wave foreshocks differ at the two observational points. The shock is between 0.02 and 0.1 Hz periods between 10 and 50 s. Consequently, at P1 and they are more intense.

Ion distributions vary from FABs (at P1) and gyrating ions (at P2) upstream of the shock, to intermediate, and finally to diffuse distributions just before the shock arrival. The FABs and the gyrating ions are observed in the absence of any ULF fluctuations, while the diffuse ions coincide with partially compressive ULF waves.

The energies of the FABs in the shock rest-frame are of the order of 20 keV, which is much more than in the case of the Earth’s bow shock, where they are $\gtrsim 10$ keV. This is probably a consequence of larger curvature radii of IP shocks and longer connection times of IMF lines to the IP shock surface. Under these conditions ions travel larger distances with $\theta_{bn} < 60^\circ$, meaning that the shock drift and shock surfing mechanisms (Hudson & Kahn 1965; Lever et al. 2001) accelerate them to higher energies.

In addition to the curvature radius and $M_A$, there are other factors that influence the efficiency of ion acceleration at shocks, such as background turbulence and plasma beta. One should also keep in mind that the quasi-perpendicular, super-critical shocks undergo continuous self-reformation, and this shock nonstationarity additionally impacts the ion reflection and energization (e.g., Lobzin et al. 2007; Yang et al. 2009; Mazelle et al. 2010).

The energies of the observed diffuse ions are $\gtrsim 200$ keV, which is similar to ions near the Earth’s bow shock.

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Appendix A

Contents

This section contains information on how the combined ion omni-directional spectra and three-dimensional particle distribution functions were obtained from the data from the ESA and SST instruments and an explanation on their operational modes. We also show the sensitivities (one-count levels) of both instruments and compare them with the observations.

Appendix B

ESA and SST Operational Modes

The ARTEMIS ESA and SST instruments were in magnetospheric Fast Survey Mode until $\sim 19:29$ UT. After that they were in magnetospheric Slow Survey Mode. While each ESA and SST sample is always collected over one spacecraft spin period ($\sim 4$ s), during the two modes, there are differences in the angular, energy, and temporal resolutions of various downlinked data products.

During Fast Survey, we have three-dimensional ESA “full mode” ion distributions (88 angles, 32 energies) available every 32 spins ($\sim 2.1$ minutes) and “reduced mode” ion distributions (50 angles, 24 energies) available for every spin. SST “full mode” ion distributions (64 angles, 16 energies) are also available for every spin.

During Slow Survey mode, ESA “full mode” ion distributions are available every 128 spins ($\sim 9$ minutes), and “reduced/omni-directional” distributions (1 angle, 32 energies) are available every spin. SST “full mode” ion distributions are available every 64 spins ($\sim 4.3$ minutes) and “reduced/omni-directional” distributions (1 angle, 16 energies) are available for every spin.

The mode change may sometimes result in a minor data loss of some products. Note also that some ground calibrations are only possible for the higher angular resolution data products.

Appendix C

Combined Omni-directional Ion Spectra and Three-dimensional Ion Distributions

The high time-resolution omni-directional ion spectra shown in Figure 2 of this study were constructed in the following way. During the early part of the interval, when the spacecraft were in Fast Survey mode, we plotted the spectra of ESA reduced mode distributions and SST full mode distributions in the same panel (no interpolation, as evidenced by the small white horizontal gap). During the later part of the interval, when the spacecraft were in Slow Survey mode, we plotted the ESA and SST reduced/omni-directional distributions in the same panel (no interpolation). There were minor losses of the reduced/omni-directional data products during the mode change, which manifest as the white gaps in Figures 2(a) and (d).

To make the ion distribution slices shown in Figure 3, we have combined the ESA and SST full mode (highest energy and angular resolution) measurements using 3D interpolation. (Note that the cadence at which these measurements are available depends on which Survey mode the instruments were in, as described above.) These types of combined distributions have recently been used in several ARTEMIS/ THEMIS studies of different plasma regions (see, e.g., Hietala et al. 2015, 2017; Runov et al. 2015; Dorfman et al. 2017). We first removed the bins that were at or below the one-count level from the measurements. We then combined the (cleaned-up) ESA and SST measurements by interpolating in 3D across the energy gap (at 25 keV) between the instruments. The lowest SST energy channels (<35 keV) on P2 were excluded from the interpolation due to degradation effects. Note that the distribution slices only show the features that are still above the one-count level after the observed (and cleaned-up) distribution has been interpolated into the slice plane.

Appendix D

Sensitivities of the ESA and SST Instruments

Figure 5 shows four one-dimensional spectra from ARTEMIS P1 spacecraft obtained at 19:15:04–19:15:08 UT (a) and 20:13:49–20:13:53 UT (b) and from P2 spacecraft at

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19:17:19–19:17:23 UT (b) and 20:13:56–20:14:01 UT (d) on 2013 October 8. Red and blue diamonds show measurements of the ESA and SST instruments, respectively. The red dashed lines and blue dashed–dotted lines represent one-count levels of the ESA and SST, respectively. We mark FAB and gyrating ions in panels (a) and (b).

We see that, on average, the sensitivity of the ESA instruments does not permit the detection of the suprathermal ions with energies between 2 and 20 keV for the IP shock studied here. Similarly, the SST instrument does not observe ions with energies above 200 keV.

Figure 5. 1D spectra obtained by ARTEMIS P1 spacecraft at 19:15:04–19:15:08 UT (a) and 20:13:49–20:13:53 UT (c) and by P2 spacecraft at 19:17:19–19:17:23 UT (b) and 20:13:56–20:14:01 UT (d) on 2013 October 8. Red and blue diamonds represent ESA and SST data, respectively. The red dashed lines represent the one-count level of the ESA instrument and the blue dashed–dotted lines show the one-count level of the SST instrument. Vertical dashed black lines delimit ESA data from SST data. FAB and gyrating ions are marked in panels (a) and (b).

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