Interstellar He$^+$ ring-beam distributions: Observations and implications

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[1] We report systematic measurements of the distribution of the incident angle of interstellar pickup He$^+$ ions as observed by STEREO/Plasma and Supra-Thermal Ion Composition (PLASTIC). We have organized these observations according to the angle spanned by the Interplanetary Magnetic Field (IMF), $\vec{B}$, and the bulk solar wind velocity, $\vec{v_{sw}}$. Our measurements show clear evidence of a relatively local injection of He$^+$ pickup ions into the solar wind, which are then seen as a ring distribution perpendicular to $\vec{B}$. Changes of the spectral shape and a reduced flux of interstellar He$^+$ during radial IMF configuration, as observed by, e.g., Ulysses/Solar Wind Ion Composition Spectrometer (SWICS), SOHO/Charge Time-Of-Flight (CTOF), Active Magnetospheric Particle Tracer Explorers/SUprathermaL Energy Ionic Charge Analyzer (SULEICA), have generally been attributed to inefficient scattering across 90° pitch-angle. Our observations of the pitch-angle distribution of interstellar He$^+$ suggest that these changes are instead a result of locally injected pickup ions that escape detection for IMF configuration in which the Solar Wind Sector of PLASTIC, as well as SWICS, CTOF, and SULEICA, are not sensitive to the measurement of the locally injected pickup ion ring. **Citation:** Drews, C., L. Berger, R. F. Wimmer-Schweingruber, and A. B. Galvin (2013), Interstellar He$^+$ ring-beam distributions: Observations and implications, *Geophys. Res. Lett.*, *40*, 1468–1473, doi:10.1002/grl.50368.

1. Introduction

[2] Interstellar pickup ions are created when inflowing interstellar neutral atoms get ionized by solar UV radiation, charge exchange with solar wind protons, or, more rarely, electron impact. Once ionized, they feel the electro-magnetic force due to the Interplanetary Magnetic Field (IMF), which is frozen into the magnetized solar wind. This leads to a gyro orbit motion around the ion's guiding center. In the following discussion, we neglect the small influence of the velocity of interstellar neutrals ($v_{\mathrm{ISM}} \sim 25$ km/s), that would slightly alter the observed speed v_{P} of pickup ions after their injection. Their initial velocity, v_{P}, after the injection process depends on the magnetic field orientation and follows $v_{\mathrm{P}} = \cos(B_\phi)\cos(B_\theta)v_{\mathrm{sw}}$, where B_ϕ and B_θ are the in-ecliptic and out-of-ecliptic magnetic field angles with respect to $\vec{v_{\mathrm{sw}}}$, the predominant solar wind velocity vector. This means that during radial magnetic field configurations ($B_\phi, B_\theta = 0$), pickup ions have, in a close-to resting frame of reference (e.g., an Earth-orbiting observer), a velocity of $v_{\mathrm{P}} = 0$ and cannot be detected [e.g., *Gloeckler et al.*, 1995; *Isenberg*, 1997]. In Figure 1, an illustration of the initial ring-beam distributions of freshly ionized helium for three non-radial magnetic field orientations is shown (arrows, red: $B_\phi = 45°$, blue: $B_\phi = 67°$, black: $B_\phi = 90°$). Directly after their ionization, pickup ions are moving on gyro orbits perpendicular to $\vec{B}$, which in Figure 1 are shown as thick dashed lines in velocity space with respect to the solar wind bulk. Note that only the projection onto the ecliptic plane of the ring-beam distributions is shown, which in three dimensions would be a two-dimensional ring perpendicular to $\vec{B}$ with a radius of v_{P}. Due to PLASTIC's limited angular acceptance in the ecliptic plane (gray shaded area in Figure 1), the initial ring-beam distribution can only be observed during magnetic field orientations where $67° < |B_\phi| < 113°$.

[3] After the injection, the pickup ion population radially diverges with the solar wind and appears to cool adiabatically with a cooling index of $\gamma = 1.35 \pm 0.2$ similar to an expanding ideal gas [e.g., *Saul et al.*, 2009; *Vasyliunas and Siscoe*, 1976]. However, the nature of this deceleration is not yet understood and still under debate. *Vasyliunas and Siscoe* [1976] also assumed that the initial anisotropic ring-beam distribution is quickly scattered into an almost isotropic shell distribution in the solar wind frame. Recent studies by, e.g., *Gloeckler et al.* [1995] and *Möbius et al.* [1998] have found that this assumption may not be exact, as the overall observed pickup flux depends on the magnetic field direction as well as the power in magnetic wave fluctuations [*Saul et al.*, 2007]. A "Hemispheric Model" proposed by *Isenberg* [1997] and a "Two-Stream Model" proposed by *Möbius et al.* [1998], that both introduced the assumption of ineffective scattering of interstellar pickup ions across 90° pitch-angle, allowed to explain most of the found dependencies of the pickup ion flux and velocity distribution function on the magnetic field configuration. They also found that pickup ions are generally not immediately isotropized and can have mean free paths as large as 1 AU.

[4] In order to provide observational evidence for these models, a direct measurement of the velocity vector $\vec{v_{\mathrm{P}}}$ of interstellar pickup ions is required [*Saul et al.*, 2007]. To our knowledge, the only study able to support these models with observations of $\vec{v_{\mathrm{P}}}$ is by *Oka et al.* [2002]. Using data from the plasma and magnetic field experiments

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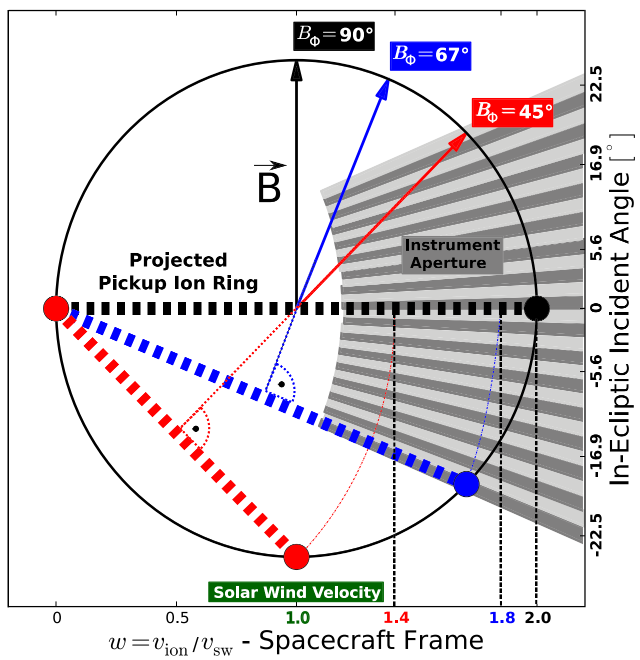

Figure 1. Illustration of pickup ion ring-beam distributions in phase space (the x axis points in the direction of the moving solar wind at $v_z = 0$ km/s, i.e., in the ecliptic plane). Using the simplification that $v_{\rm ISM} = 0$ km/s, freshly ionized interstellar pickup ions start to gyrate perpendicular to $\vec{B}$ with a maximum velocity of twice the solar wind velocity. The resulting velocity distribution function is often referred to as ring-beam distribution (thick dashed lines) and can be described to be a result of a two-dimensional cut at $v_p = 0$ km/s perpendicular to $\vec{B}$ through a spherical shell (black outer circle) with a radius of $r = v_{\rm sw}$. Due to the ion's perpendicular motion around the solar magnetic field vector $\vec{B}$ and PLASTIC's limited angular acceptance, observations of freshly ionized pickup ions are confined to in-ecliptic magnetic field angles between $67° < |B_\phi| < 113°$, i.e., ranges in which the resulting ring-beam distribution is covered by the instrument's aperture (gray shaded area).

aboard Geotail, they were able to show that the velocity distribution function of interstellar He^+ pickup ions sometimes resembles the form of a torus, which in the literature is often referred to as "ring-beam distribution". They also found that the occurrence rate of this torus-shape velocity distribution function is linked to the magnetic field direction and turbulence levels similar to what was observed in [*Saul et al.*, 2007] for the pickup ion flux. Unfortunately, their observations lack the required angular resolution and collection power to resolve the relation between $\vec{v}_{\rm P}$ and the IMF $\vec{B}$ and thus could not provide conclusive evidence for the aforementioned pickup ion models. Other instruments were also unable to provide the required measurements of $\vec{v}_{\rm P}$ with sufficient collection power [Ulysses/Solar Wind Ion Composition Spectrometer (SWICS)] or angular resolution [SOHO/Charge Time-Of-Flight (CTOF), which also lacks a co-located IMF measurement].

[5] Here, we report observations of the instantaneous pitch-angle distribution of He^+ during intermediate cases of quasi-perpendicular and -parallel IMF configurations with respect to $\vec{v}_{\rm sw}$. This has allowed us to fill the aforementioned gap and to reveal for the first time the relation between $\vec{v}_{\rm P}$ and $\vec{B}$. Our result questions the prevalent assumption that ineffective scattering across 90° pitch-angle leads to the changes of the flux and spectral shape of interstellar He^+ during quasi-radial IMF orientations as was observed by *Isenberg* [1997], *Saul et al.* [2007], and *Möbius et al.* [1998].

2. Instrumentation and Data Acquisition

[6] In this study, we report on observations of He^+ pickup ions with the Plasma and Supra-Thermal Ion Composition (PLASTIC) instrument [*Galvin et al.*, 2008] aboard the Solar TErrestrial RElations Observatory (STEREO A) during varying alignments of the IMF vector $\vec{B}$. PLASTIC is a time-of-flight mass spectrometer and combines measurements of the particle's energy E, time-of-flight τ, and energy-per-charge E/q to determine its mass $m_{\rm ion}$, charge $q_{\rm ion}$, and velocity $v_{\rm ion}$. Our following analysis is performed with the Solar Wind Section (SWS) of PLASTIC, the entrance of which is centered around the line connecting the Sun and the spacecraft. In azimuthal direction, it utilizes a resistive anode to distinguish between 32 different incident angles of particles in form of 32 angular bins that are linearly spaced in the range of $\alpha_{\rm acc} = \pm 22.5°$ with a width of 1.4° each. In polar direction, an electrostatic deflection system is used to determine the out-of-ecliptic incident angle of particles, which again are binned into 32 so-called deflection steps that are linearly spaced in the range $\beta_{\rm acc} = \pm 20.0°$ with a width of 1.3° each. In total, the SWS of PLASTIC covers $\sim \pi/2$ steradians and is able to resolve angular features $> 1.3°$– a key feature for the following analysis.

[7] Following the approach of *Drews et al.* [2012], we use Pulse Height Analysis data to create a consolidated He^+ count rate that contains for each incident He^+ measurement information on its in- and out-of-ecliptic incident angle (α, β), its velocity $v_{\rm ion}$, the averaged solar wind speed $v_{\rm sw}$, and the averaged IMF direction (B_ϕ, B_θ) within 5 min intervals. With $v_{\rm ion}$ and $v_{\rm sw}$, we can derive the dimensionless quantity $w = v_{\rm ion}/v_{\rm sw}$, which denotes the total velocity of He^+ with respect to $v_{\rm sw}$ in a resting frame of reference (see Figure 1). However, with respect to the solar wind bulk velocity, pickup ions are initially injected onto a spherical shell with $r = v_{\rm sw}$ (black circle, Figure 1) at $w = 0$ where they are forced into a gyro motion around $\vec{B}$ resulting in the characteristic pickup ion ring distributions (thick dashed lines, Figure 1). The relative velocity of pickup ions with respect to the outward flowing solar wind packet $w_{\rm sw}$ is then given by

$$w_{\rm sw} = \sqrt{w^2 - 2 \cdot w \cdot \cos(\alpha)\cos(\beta) + 1}, \qquad (1)$$

as illustrated in Figure 1. Here, α denotes the in-ecliptic and β the out-of-ecliptic incident angle of the ion.

[8] We obtained the average in- and out-of-ecliptic IMF angles B_ϕ and B_θ with 1 min time resolution (B_ϕ is defined in Figure 1, $-90° < B_\theta < 90°$ is measured from the ecliptic plane) from the magnetometer of the In situ Measurements of Particles and coronal mass ejection Transients (IMPACT) instrument suite [*Acuña et al.*, 2008] aboard STEREO A. We performed our analysis on the quiet solar wind observed between March 2007 and December 2009. In order to derive

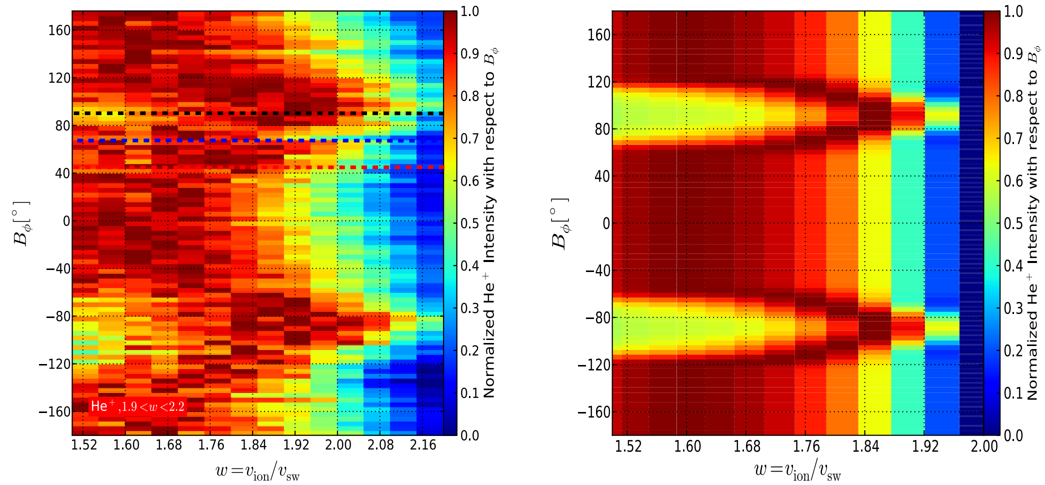

Figure 2. (Left panel) He$^+$$w$-spectra ($x$ axis) measured as a function of the in-ecliptic magnetic field angle B_ϕ (y axis) between March 2007 and December 2009 with STEREO/PLASTIC. The intensity of the He$^+$$w$-spectra ($\Delta w_{\text{bin}} = 0.04$) is normalized to the maximum of each $B_{\phi,\text{bin}}$ ($\Delta B_{\phi,\text{bin}} = 4°$). The black, blue, and red dashed lines represent IMF configuration as sketched in Figure 1. (Right panel) Modeled He$^+$$w$-spectra ($x$ axis) as a function of the in-ecliptic magnetic field angle B_ϕ (y axis).

He$^+$ w-spectra as a function of the in-ecliptic magnetic field angle B_ϕ, we constrain our He$^+$ rate, to time periods where, within a 30-min time frame, the standard deviation of the averaged interplanetary magnetic field was smaller than 10°, i.e., $\Delta B_\phi, \Delta B_\theta < 10°$. Furthermore, we only consider time periods from now on, where $-10° < B_\theta < 10°$, i.e., time periods where the solar magnetic field vector is confined to the ecliptic plane. This leaves us with $1.6 \cdot 10^6$ He$^+$ events that are distributed among $4 \cdot 10^4$ unique 5 min intervals.

[9] The derived He$^+$ w-spectra as a function of the in-ecliptic magnetic field angle B_ϕ are shown in Figure 2, left panel. Because B_ϕ is non-uniformly distributed over time, the data are normalized to the maximum of each concurrent $B_{\phi,\text{Bin}}$ with a width of 4°. It appears that during periods where $67° < |B_\phi| < 113°$, changes of the IMF orientation are accompanied by changes of the observed w-spectra. During quasi-perpendicular orientations of the IMF, the He$^+$ w–spectra show a relatively steep distribution function with a cut-off at $w \geq 2.0$, which transitions into a continuous decay with a cut-off at $w < 2.0$. Outside $67° < |B_\phi| < 113°$, i.e. during quasi-parallel orientations of the IMF, the He$^+$$w$-spectra seem to be flatter and not to change with a changing IMF orientation. The shape of the w–spectra is also illustrated in Figure 3, where three He$^+$ count rate w-spectra are shown for the three different IMF orientation sketched in Figure 1.

[10] In analogy to the He$^+$ w-spectra, we create distributions of the in-ecliptic incident angle of He$^+$ α for $1.9 < w < 2.2$ (This w-constrain reduces our statistics further to $3.5 \cdot 10^5$ counts distributed among $3.6 \cdot 10^4$ unique time intervals). We have binned the He$^+$$w$-spectra at $1.9 < w < 2.2$ into a 2-D $B_\phi - \alpha$ grid with bin widths of $B_{\phi,\text{Bin}} = 4°$ and $\alpha_{\text{Bin}} = 2.8°$, which is shown in Figure 4, left panel. We needed to correct for an instrumental effect, as the distributions of in-ecliptic incident angles as seen from PLASTIC already show a strong anisotropy due to a nonlinear efficiency function of the underlying position detection by the resistive anode. To correct this effect and derive the real distribution of He$^+$ incident angles, we assume that the He$^+$ velocity distribution is fully isotropic during radial magnetic field configurations as was proposed by *Isenberg* [1997] and *Möbius et al.* [1998]. Under these conditions, the out-of-ecliptic incident angles β, which do not show any efficiency drift, are believed to show the same distribution as α. We used these periods to correct the nonlinear efficiency drift of α and to derive the distribution of the in-ecliptic incident angles of He$^+$ as a function of B_ϕ, which are shown in the left panel of Figure 4. Similar to the observed He$^+$ w-spectra, the distributions of incident angles seem to be a

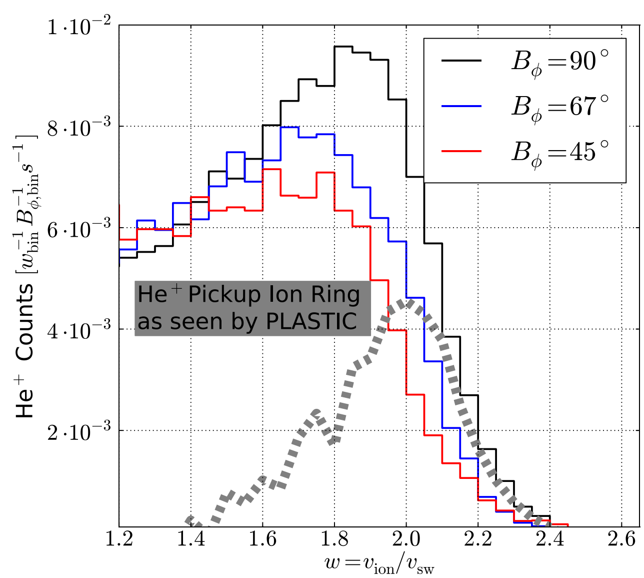

Figure 3. Averaged He$^+$ count rate w-spectra for three different IMF orientations as shown in Figure 1 (black, blue, and red lines). The dashed gray line shows the absolute difference of the He$^+$ w-spectrum between periods where PLASTIC is sensitive to the measurement of the He$^+$ pickup ion ring (black) and not sensitive (red).

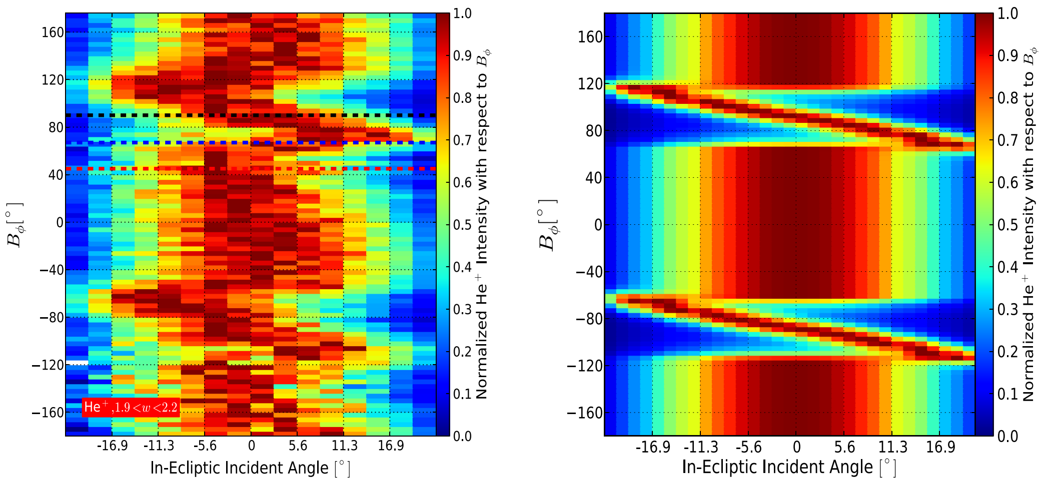

Figure 4. (Left panel) Distributions of the angle of incidence, α, of interstellar He^+ ions measured as a function of B_ϕ in the w-range $1.9 < w < 2.2$ with STEREO/PLASTIC. The x axis shows the incident angle α and the y axis the in-ecliptic magnetic field angle B_ϕ. The angular distribution is normalized to the maximum of each $B_{\phi,\mathrm{Bin}}$. The black, blue, and red dashed lines represent magnetic field configuration as sketched in Figure 1. (Right panel) Modeled distribution of the angle of incidence of interstellar He^+ as a function of the in-ecliptic magnetic field angle B_ϕ (y axis).

clear function of B_ϕ during periods where $67° < |B_\phi| < 113°$, i.e., changing linearly with B_ϕ between the two outermost bins at $\alpha = \pm 22.5°$. Outside these periods, the distributions of incident angles seem to be centered around $\alpha = 0°$ and show no dependency on B_ϕ.

3. Data Interpretation

[11] The observed w-spectra of He^+ during periods of a relatively constant magnetic field direction show a clear dependency on the in-ecliptic magnetic field angle B_ϕ (see Figure 2, left panel). The typical w-cutoff during a perpendicular alignment of $\vec{B}$ with respect to $\vec{v_{\mathrm{sw}}}$ lies at $w \approx 2.1$. During configurations with $\vec{B}$ parallel to $\vec{v_{\mathrm{sw}}}$, the observed w-spectra show a significantly smoother decay towards the cutoff as was independently observed by *Gloeckler et al.* [1995], *Möbius et al.* [1998], and *Saul et al.* [2007]. Without consideration of the Eigen-velocity, v_{ISM}, of interstellar neutrals or additional particle acceleration, the injection process sketched in Figure 1 would produce a sharp cutoff at $w = 2$, which drops to $w = 1.84$ at in-ecliptic magnetic field angles of $|B_\phi| = 67°, 113°$ (see equation (1)). Outside the range of $67° < |B_\phi| < 13°$, PLASTIC is not able to observe the in situ injection of pickup ions and is only susceptible to the pickup ion component that has undergone pitch-angle scattering by magnetic fluctuations (see Figure 1). However, in periods where $67° < |B_\phi| < 113°$, one expects the in situ incident angles of He^+ to be a function of B_ϕ, i.e., changing linearly between $\alpha = -22.5°$ at $|B_\phi| = 67°$ to $\alpha = 22.5°$ at $|B_\phi| = 113°$ as a result of the direct observation of the interstellar pickup ion ring.

[12] To filter for freshly ionized He^+, we used data in a w-range of $1.9 < w < 2.2$. The reason to use such a broad w-range is that several effects, e.g., acceleration processes in the heliosphere or a nonzero injection speed of interstellar neutrals, can add a significant uncertainty to the expected velocity of interstellar pickup ions and thus make it rather difficult to give a precise prediction for the velocity of freshly ionized pickup ions with respect to the bulk solar wind. However, it is suffice to say that He^+ ions in this w-range most likely represent particles that have not undergone significant cooling, i.e., particles that have almost exclusively been freshly ionized, with only small contributions of the cooled pickup ion population.

[13] Figure 4 (left panel) shows the observed in-ecliptic angles of incidence of freshly ionized He^+, which behave as one would expect from Figure 1. For $B_\phi = (67°, -113°)$ the distribution of α shows a strong anisotropy up to the outermost edge of the instrument's aperture at $\alpha = -22.5°$ and changes linearly with B_ϕ up to $\alpha = 22.5°$ for $B_\phi = (113°, -67°)$. We interpret these observations as a direct measurement of a freshly injected pickup ion ring that traverses the instrument's aperture in a narrow angular range perpendicular to B_ϕ as illustrated in Figure 1 by the thick dashed lines. For all other magnetic field orientations, the distributions of He^+'s in-ecliptic incident angles seem to be centered around $\alpha = 0°$ and are, as we will show in a moment, consistent with an isotropic pickup ion shell distribution.

[14] To verify our results, we use a highly simplified model to reproduce the observed dependencies of w and α on the magnetic field direction, B_ϕ, as seen in the left panels of Figures 2 and 4. For that, we start with an isotropic He^+ velocity distribution function $\Psi(w_{\mathrm{sw}})$ adapted from *Vasyliunas and Siscoe* [1976] in the upwind region of the Sun. To satisfy observations reported in this paper (Figure 3) and those made by the Suprathermal Energy Ionic Charge Analyzer [*Möbius et al.*, 1998], which observed during a radial IMF orientation a relatively continuous decay of the He^+ w-spectra towards $w \approx 2$, we further deplete $\Psi(w_{\mathrm{w}})$ at $w_{\mathrm{sw}} \leq 2$ using

$$\Psi(w_{\mathrm{sw}})_{\mathrm{D}} = \Psi(w_{\mathrm{sw}}) \cdot E(w_{\mathrm{sw}}, 0, 0.5),$$

where $E(x, x_0, \sigma) = \exp(0.5 \cdot ((x - x_0)/\sigma)^2)$. This models an isotropic interstellar shell-like pickup ion velocity distribution function, which has already been cooled to

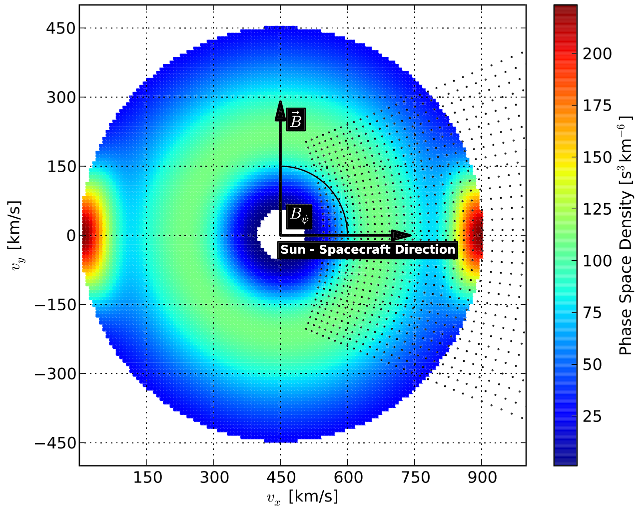

Figure 5. A 2-D cut of the model He^+ phase space density in the (v_x, v_y) plane at $v_z = 0$ km/s for the situation in which $\vec{B} \perp v_{sw}$ and $v_{sw} = 450$ km/s. It shows an isotropic pickup ion shell distribution (inner green ring at ~ 250 km/s) superposed with a freshly injected pickup ion ring perpendicular to $\vec{B}$ at $w_{sw} = 1$. The gray dots in each panel represent the location of phase space covered by the PLASTIC instrument. This model, but for all possible orientations of $\vec{B}$, is used for the simulations shown in the right-hand panels of Figures 4 and 2 for varying IMF orientations.

lower w. In the second step, we superpose on this shell distribution a freshly injected pickup ion ring distribution,

$$\Psi(w_{sw}, B_\phi)_P = \Psi(w_{sw}) \cdot E_a(w_{sw}, 1, 0.1) \quad (2)$$

$$\cdot E_b(\cos(\pi - B_\phi), 0, 0.1), \quad (3)$$

to obtain a general representation of the He^+ velocity distribution, which includes a freshly injected pickup ion ring at $w = 2$ (as observed in Figure 3 and accomplished through E_a), which is localized in a narrow angular range perpendicular to B_ϕ (accomplished through E_b) as illustrated in Figure 1. The final model for the He^+ velocity distribution function is then

$$f(w_{sw}, B_\phi) = \Psi(w_{sw})_D + \Psi(w_{sw}, B_\phi)_P, \quad (4)$$

which is shown in Figure 5 for $B_\phi \perp v_{sw}$. We note that it is not our intention to give an explanation but rather an impression of the form of the He^+ distribution function. Our parameters for the model are therefore mainly deduced from our observation of the pickup ion ring shown in Figure 3 instead of being physically motivated. However, our model may be used as a first reference point for further studies on the distribution function of interstellar pickup ions.

[15] In order to derive the expected w-spectra and α-distribution as seen from PLASTIC, we need to convolve $f(w_{sw}, B_\phi)$ with the respective instrument response function. This allows us to derive the expected counts per second for each instrumental incident angle (α, β) and energy per charge step i

$$C\left(v^i_{ion}, \alpha, \beta\right) = f(w_{sw}, B_\phi) \cdot V_P^{i,\alpha,\beta} \cdot V_S^{i,\alpha,\beta}, \quad (5)$$

where $C\left(v^i_{ion}, \alpha, \beta\right)$ is the expected count rate, $V_P^{i,\alpha,\beta}$ the velocity space volume (gray dots in Figure 5), and $V_S^{i,\alpha,\beta}$ the position space volume, which are defined as

$$V_P^{i,\alpha,\beta} = \left(v^i_{ion}\right)^2 \sin(\beta)\Delta v_i \Delta\beta\Delta\alpha$$
$$V_S^{i,\alpha,\beta} = v^i_{ion} A^{\alpha}_{act}.$$

Here, A_{act} denotes the active area of the Solar Wind Section, while V_P and V_S span the volume in phase space that PLASTIC can observe.

[16] With equations (4) and (5), we can now determine the expected w-spectra and α-distribution from the velocity distribution function shown in Figure 5 as a function of the in-ecliptic magnetic field angle B_ϕ. We show these model distributions in the right-hand panels of Figures 2 and 4 as a direct comparison to our observations, which are shown in the left-hand panels of Figures 2 and 4. For the expected w-spectra in Figure 2, we had to use instrumental logarithmically spaced w-bins contrary to our observations, where we could use linearly spaced w-bins due to the mixture of many solar wind velocities.

[17] Although equation (5) is a simplified version of the instrumental response function, we can already qualitatively reproduce our observation from Figure 2, left panel. More importantly, our model for the He^+ velocity distribution function with a pickup ion injection ring perpendicular to $\vec{B}$ can clearly reproduce our observations shown in Figure 4, left panel.

4. Conclusion

[18] Interstellar pickup ions, which are believed to be injected as a ring-like velocity distributions into the bulk solar wind, are exposed to fluctuations of the IMF and thus undergo pitch-angle scattering. It is generally assumed that this process can be very efficient on short time scales, and thus velocity distributions of pickup ions were believed to be fully isotropic in nature [*Vasyliunas and Siscoe*, 1976]. However, unambiguous evidence for this assumption has yet to be found. Indeed, observations of reduced one-dimensional w-spectra for quasi-parallel and -perpendicular IMF orientations revealed a significant difference in flux and spectral shape of interstellar He^+ pickup ions, which e.g., *Saul et al.* [2007], *Möbius et al.* [1998], and *Isenberg* [1997] attributed to ineffective scattering across 90° pitch-angle.

[19] Our analysis of the in situ pitch-angle distribution of He^+ with PLASTIC aboard STEREO A revealed a highly isotropic population of cooled interstellar pickup ions. Superposed onto this population, we found an almost scatter-free pickup ion population that follows a strict gyro motion perpendicular to $\vec{B}$, which we interpret to be a direct imprint of the injection of freshly ionized interstellar helium into the bulk solar wind. Thus, we could show that interstellar pickup are not fully isotropic and instead show distinct anisotropies resulting from the pickup process.

[20] The locally injected interstellar He^+ pickup ion ring exhibits a significantly different behavior than the isotropic component in terms of pitch-angle and w-distribution and strictly follows the concurrent orientation of the IMF. However, observation of this population can only be made during IMF orientation, where PLASTIC is sensitive to a freshly injected pickup ring, i.e., $67° < |B_\phi| < 113°$. During these periods, we observed a highly anisotropic distribution

of He^+ incident angles that were accompanied by distinct changes of the observed shape of He^+ w-spectra with B_ϕ. As sketched in Figure 1 and shown in Figure 3, this naturally causes the He^+ w-spectra to be a function of the instrumental incident angle α, as described in equation (1). A highly simplified model of the He^+ velocity distribution that includes a freshly injected pickup ion ring superposed onto a cooled, isotropic pickup ion model (based on theoretical work from *Vasyliunas and Siscoe* [1976]) was able to reproduce our observations strikingly well (see Figures 4 and 2). In view of our current findings, independent observations made by Ulysses/SWICS [*Gloeckler et al.*, 1995], SOHO/CTOF [*Saul et al.*, 2007], and AMPTE/SULEICA [*Möbius et al.*, 1998] of a significantly reduced flux and much smoother decay of the observed interstellar pickup ion w-spectra cannot be solely explained by ineffective scattering across 90° pitch-angle. In fact, our observations strongly suggest that these observations are the result of a relatively scatter-free pickup ion ring that, during many IMF orientations, escapes detection. However, a relatively smooth decay towards $w = 2$ of the isotropic He^+ w-spectra, as evidenced by the aforementioned observations and this publication, is necessary in our simplified model to fully reproduce our observations.

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