Observations of the He^+ Pickup Ion Torus Velocity Distribution Function with SOHO/CELIAS/CTOF

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Abstract. Interstellar PickUp Ions (PUIs) are created from neutrals coming from the interstellar medium that get ionized inside the heliosphere. Once ionized, the freshly created ions are injected into the magnetized solar wind plasma with a highly anisotropic torus-shaped Velocity Distribution Function (VDF). It has been commonly assumed that wave-particle interactions rapidly destroy this torus by isotropizing the distribution in one hemisphere of velocity space. However, recent observations of a He^+ torus distribution using PLASTIC on STEREO showed that the assumption of a rapid isotropization is oversimplified. The aim of this work is to complement these studies. Using He^+ data from the Charge Time-Of-Flight (CTOF) sensor of the Charge, ELement, and Isotope Analysis System (CELIAS) on-board the SOlar and Heliospheric Observatory (SOHO) and magnetic field data from the Magnetic Field Investigation (MFI) magnetometer of the WIND spacecraft, we derive the projected 1-D VDF of He^+ for different magnetic field configurations. Depending on the magnetic field direction, the initial torus VDF lies inside CTOF's aperture or not. By comparing the VDFs derived under different magnetic field directions with each other we reveal an anisotropic signature of the He^+ VDF.

INTRODUCTION

PickUp Ions (PUIs) in the heliosphere are former neutrals that have been ionized by solar EUV radiation, charge-exchange with solar wind protons, or electron impact. The most common seed population of PUIs are neutrals from the interstellar medium that penetrate the heliosphere unimpeded by electro-magnetic forces. Interstellar PUIs were first observed by Möbius *et al.* [1] using data from the AMPTE spacecraft and their nature has been a subject to research ever since (cf. [2]). The neutrals have commonly a very low speed compared to the solar wind, which leads to an anisotropic initial Velocity Distribution Function (VDF) once the neutrals are ionized. They are forced on gyro orbits perpendicular to the ambient magnetic field that is swept outward with the solar wind. Thus the initial VDF resembles the form of a torus in velocity space (cf. Drews *et al.* [3]). Considering a perpendicular magnetic field configuration the speed of PUIs in the spacecraft frame of reference would range between $w \doteq \frac{v_{\mathrm{ion}}}{v_{\mathrm{sw}}} \approx 0$ and $w \approx 2$, which is why PUI VDFs show a strict cutoff at $w \approx 2$.

This torus VDF is then altered by wave-particle interactions and cooling processes. Wave-particle interactions can change the pitch-angle of PUIs which leads to an isotropization of the VDF. It has been commonly assumed that the isotropization happens on a short timescale compared to the time it takes the PUIs to reach the observer. Therefore, observations of an anisotropy in He^+ VDFs were previously attributed to inefficient pitch-angle scattering across 90° [4]. But studies of Oka *et al.* [5] and Drews *et al.* [6]showed that the anisotropy stems from locally ionized PUIs that are not yet isotropized and still exhibit a torus-like VDF.

DATA ANALYSIS

The aim of this study is to show that an anisotropic torus feature of the He^+ PUI VDF is also observed with the CTOF sensor on-board SOHO. To this aim we combine data measured by the CTOF sensor with data provided by the MFI instrument of the nearby WIND spacecraft.

He^+ Pickup Ion Data

CTOF is a linear time-of-flight mass spectrometer which measures energy-per-charge, time-of-flight and residual energy of incoming ions which can then be converted into their mass-per-charge, mass, and energy. A more detailed description of the CTOF sensor can be found in Hovestadt *et al.* [7]. Due to the rather short operation time of CTOF, only data from day of year 150 to 220, 1996, is used. During this time SOHO was located at the upwind side of the sun with respect to the interstellar neutral flow, the region of PUI crescent [8].CTOF's aperture covers a field of view of $\pm 25°$ in-ecliptic and $\pm 15°$ out-of-ecliptic while pointing directly towards the sun. We apply the same algorithm for the conversion of energy-per-charge and time-of-flight into mass-per-charge, $\frac{M}{Q}$, values that was already used in Taut *et al.* [9], with the difference that it has been adapted to the energy loss of helium ions. Similar to the work based on data from the PLASTIC instrument on STEREO/A by Drews *et al.* [6] we identify He^+ ions by a simple mass-per-charge box fulfilling the criterion $3.5 \leq \frac{M}{Q} \leq 4.5$. We only consider the VDF in a range between $w_{\mathrm{He}^+} = 1.3$ and $w_{\mathrm{He}^+} = 2.3$. At this speed range no background of prominent heavy solar wind ions is expected.

B-Field Extrapolation

The MFI instrument on-board WIND measures the magnetic field vector (for example in GSE coordinates: B_x, B_y, and B_z) at a maximum frequency of 10.9 Hz [10]. As both spacecraft, SOHO and WIND, are approximately located at L1, the magnetic field vector at the location of WIND should not be that far off the ambient magnetic field vector at the location of SOHO. However, assuming a magnetic field that is frozen into the solar wind plasma, one can calculate the time difference, Δt, with which the same magnetic field is seen by the two spacecraft by convecting the magnetic field from one spacecraft to the other (as used in e.g. Saul *et al.* [11]). We then assume the magnetic field vector measured by WIND/MFI corrected for this time difference ($\Delta t \sim 30$ min) to be valid at the location of SOHO.
To synchronize this data with the CTOF He^+ data we calculate the mean magnetic field vector for every 5-min measurement cycle of the sensor. Additionally, we determine the magnetic field angle with respect to the axis of CTOF's aperture, which is simply $\alpha = \arccos\left(\frac{B_x}{B}\right)$. We use this quantity to further restrict the data. The magnetic field convection approach as described above yields only reasonable result if the magnetic field does not change rapidly on short timescales [12]. Thus, we removed all 5-min cycles in which the standard deviation of α exceeds 5°. Furthermore, the standard deviation of every 5-min cycle including three cycles before and after this cycle has been determined and all cycles with a value greater than 10° were dismissed. This ensures that all possible uncertainties related to the extrapolation of the magnetic field are kept at a reasonable level.

METHOD & RESULTS

The magnetic field orientation tells us if the initial torus VDF of the He^+ PUIs can be detected with the aperture of CTOF. Using simple geometric arguments one can derive the velocity, $\vec{V}$, for which He^+ PUIs that are injected into a magnetic field $\vec{B}$ have their maximum speed in the spacecraft frame. This velocity is given by

$$\vec{V} = 2(\vec{v}_{sw} - \frac{v_{sw} B_x}{B^2}\vec{B}) \tag{1}$$

assuming a solar wind streaming radially away from the sun. We are only interested in the in- and out-of-ecliptic angles, ϕ and θ, of this velocity that, neglecting the small velocity of the neutral seed population, do not depend on the ambient solar wind speed. These angles can be calculated by

$$\phi = \arctan 2(V_y, V_x) \tag{2}$$

$$\theta = \arcsin\left(\frac{V_z}{V}\right). \tag{3}$$

Finally, we can use these angles to distinguish whether a signature of the initial torus VDF should be observed for a certain magnetic field configuration.

The initial torus VDF of He^+ ions is a 3D feature. As CTOF does not offer any information about the incident angle of measured ions we are limited to spectra that are integrated over the whole angular acceptance of the sensor. However, parts of the torus VDF are only inside CTOF's aperture during specific magnetic field orientations. This is illustrated in the three panels on the right-hand side in Fig. 1, that show the v_x-v_y plane. The expected position of the torus VDF is shown for three magnetic field configurations, and CTOF's field of view is indicated by the shaded triangle. Naturally, the count rates near the cutoff speed, $w \approx 2$, should be increased if the torus is inside the covered velocity space in contrast to configurations where it lies outside this area. In the latter case only He^+ ions that have already gone through a scattering process are measured by CTOF. We chose the magnetic field configuration according to the following conditions: the torus signature lies in the center, at the edge, or just outside the aperture. Additionally we consider magnetic field orientations where absolutely no torus distributed He^+ ions should be measured at all, which means that only ions that have already been isotropized are measured. The detailed criteria for these configurations are summarized in Tab. 1. The neutral seed population of the He^+ ions has a non-negligible speed, which effects

TABLE 1. Magnetic field configurations and corresponding positions of the He^+ torus in CTOF's aperture. These restrictions are used to create the histograms displayed in Fig. 1

Torus position	$\lvert\phi\rvert/°$	$\lvert\theta\rvert/°$
Center of aperture	0 – 7.5	≤ 10
Edge of aperture	15 – 22.5	≤ 10
Just outside	30 – 37.5	≤ 10
Outside	≥ 50	-

the cut-off of the PUI VDF. This means that for different solar wind speeds, the cut-off is located at a slightly different w value. Thus, we chose to consider only a comparatively narrow solar wind speed range. This speed range is $360 \text{ km s}^{-1} \leq v_{sw} \leq 390 \text{ km s}^{-1}$, as it offers very good counting statistics.

After the restriction of the data according to the criteria described above, w-histograms of the single data sets were created. On the one hand, these histograms were corrected for the instrumental response of CTOF, on the other hand, the number of cycles that contribute to the data set was taken into account. This ensures that the histograms can be compared to each other. These histograms are shown in the top panel of Fig. 1. To reveal the initial torus VDF, the ratio of the "Center", "Edge", and "Just outside" histogram with the "Outside" histogram is displayed in the lower panel. In the error bars shown in Fig. 1, only the pure counting error was considered, which has been propagated into the ratio of the histograms. It is obviously impossible to quantify an error for the magnetic field orientation due to the lack of a direct measurement at the location of SOHO. This, of course, introduces a systematic error, which is minimized using the restrictions given in the previous section.

One can see that during magnetic field orientations where we would expect the torus to be in the center of CTOF's aperture around 2.5 times more ions are measured around $w \approx 2$ than during orientations with the torus outside the aperture. When we expect the torus to be at the edge of the aperture this ratio is reduced, and its maximum appears to be shifted towards lower w values. The lower intensity can be explained by the width of the torus which makes it possible that a part of it is not detected by CTOF. Furthermore, in Hovestadt *et al.* [7] it can be seen that the detection efficiency of CTOF decreases with increasing deviation of the incident angle from the sun-instrument line. The shift in w can easily be explained considering the 2D velocity plots displayed on the right-hand side of Fig. 1. If the torus is not located in the center of the aperture the maximum speed of the He^+ ions in the spacecraft frame of reference decresases. When going towards lower ion speeds, the torus signature fades which may be explained by the cooling of the VDF. He^+ ions measured at lower w values have already had time to cool, which means that more time for isotropizing wave-particle interactions was available.

Considering orientations with the torus just outside the aperture, no excess at higher w values is observed, which contradicts the theory of rapid isotropization in one hemisphere of velocity space, but it can easily explained by a He^+ torus. Furthermore, the ratio drops for high w in all curves. In this speed range the PUIs must have undergone an acceleration process, which seems to act predominantly parallel to the magnetic field (at least in our considered time period). The acceleration by turbulent field-aligned electric fields [13] could be an explanation for that.

In summary, we observe a clear anisotropy in the VDF of He^+ PUIs, which is in agreement with a torus VDF superposed over an isotropic VDF. The location of the torus in velocity space depends on the ambient magnetic field as discussed in Drews *et al.* [3]. Even though the extrapolated magnetic field for the location of SOHO introduces some uncertainty, we were able to confirm previous studies with our new data set. Our results challenge the assumption of rapid pitch-angle isotropization which is commonly made in PUI transport models (e.g. [14]), as this is not in agreement with our observations.

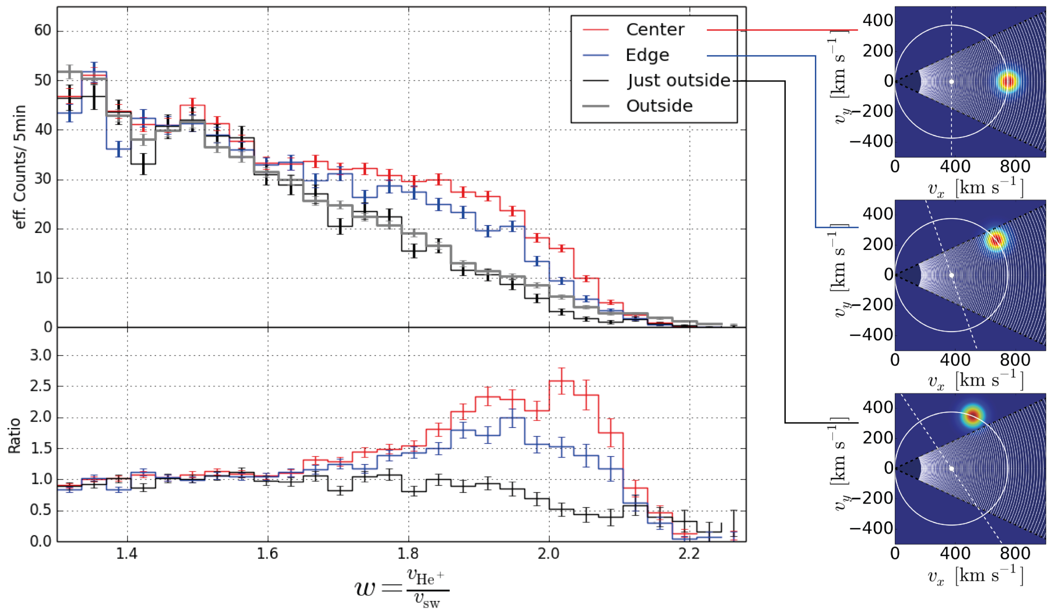

FIGURE 1. In the top panel the *w*-histograms corrected for detection efficiencies and observation time are displayed that were created for the four magnetic field configurations given in Tab. 1. The lower panel displays the ratio of the histograms ”Center”, ”Edge”, and ”Just outside” with the ”Outside” histogram to make the torus distributed He^+ ions visible. The three plots on the right-hand side show a 2D cut through velocity space, the v_x-v_y plane, which correspond to the ”Center”, ”Edge”, and ”Just outside” case. The dashed white line shows the magnetic field orientation and the expected torus distribution (with arbitrary width) indicated with a color code. The shaded triangle corresponds to CTOF’s aperture.

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