Observation of Suprathermal Tails of He\(^+\) Pickup Ions across Solar Wind Compression Regions with STEREO PLASTIC

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Abstract. The presence of suprathermal tails of solar wind and pickup ions in interplanetary space has been widely observed, even during quiet times with no simultaneous observation of solar energetic particles. One of the persistent characteristics of these tails have been power law spectra of the velocity distribution function with a \(v^{-5}\) dependence in the solar wind reference frame and exponential fall-off at higher energies, but variations in the spectra including those of other species have also been observed. Several attempts to explain the formation of suprathermal tails during quiet times have been made, among them continuing acceleration by compressive fluctuations of the solar wind and the stochastic superposition of exponential, Gaussian, and variable power law spectra from diffusive shock, stochastic, and other acceleration processes. We find here that acceleration is effective within compression regions with and without shocks. In the context of a superposed epoch analysis of the evolution of He\(^+\) pickup ion distributions across compression regions, we report on a related study of He\(^+\) tails, using STEREO PLASTIC data from 2007 through 2014. Quiet times have been selected based on limiting energetic He fluxes above the tail energies and based on the tail fluxes themselves. We find that the suprathermal tail flux is dependent on the compression strength and varies substantially across the compression region. The strongest tails with spectra somewhat steeper than \(v^{-5}\) occur in the compressed fast solar wind, and they decrease rapidly with distance from the preceding and following compression into the rarefaction region, when using an unbiased data sample and applying a quiet time criterion based on higher energy ions. This may be consistent with the compressions being a potential source of the tails. When applying a quiet time criterion based on the observed tail fluxes, the temporal evolution disappears, possibly implicating a selection of the lower end of a Poisson distribution of tail count rates, rendering such a selection unusable for temporal evolution studies.

1. Introduction
Initially, the origin of energetic particles in interplanetary space has been associated with either acceleration in solar flares or disturbances in the solar wind (SW). Coronal mass ejections (CME) and SW stream interaction regions were particularly suspected, along with their accompanying shocks [e.g. 1]. While flare related energetic particles were thought to be accelerated directly out of coronal material close to the Sun, CME and SW stream interaction related particles were thought to be accelerated out of
the SW. However, in the latter case, the requirement that ions of the source population either need a minimum speed to outrun the shock from downstream or be sufficiently mobile relative to the local bulk speed makes direct acceleration of SW a challenge, which is referred to as the injection problem [2].

Other observational challenges to the original acceleration paradigm, yet potentially mitigating the injection problem, came from composition measurements. He\(^+\) was found overly abundant in interplanetary energetic particles [3], and an unusually high $^3\text{He}/^4\text{He}$ ratio in many CME related energetic particle events, mimicking the abundance of impulsive flare particles, was reported [4]. Whereas the origin of the former abundance anomaly was unknown at first, the latter immediately implicated impulsive flares as the potential origin of the source population. Indeed, the signature of impulsive flare material was identified in the pre-interplanetary shock population, and it became clear that dependent on the phase of the solar cycle this population and thus the CME particles were more or less peppered with impulsive flare material [5]. The mystery of the huge He\(^+\) abundance resolved itself in favor of interstellar pickup ions (PUIs), when stark overabundances of He\(^+\) were found in the energetic particle populations of co-rotating interaction regions (CIR) [6], with a distinct increase towards the end of a CIR where the observer is connected to it at larger distances from the Sun [7]. Even when the $^3\text{He}/^4\text{He}$ ratio in the SW was anomalously enhanced in a CME, PUIs are accelerated and not the SW population [8]. In both cases, apparently an already more energetic particle population, or better a much wider velocity distribution in the SW is preferentially accelerated relative to the also contributing SW distribution. This scenario of an already suprathermal source population for further acceleration was briefly summarized [9] and reviewed in great detail [10].

The presence of suprathermal tails in interplanetary space even during quiet times, as selected by energetic and suprathermal particle rates below a pre-defined threshold [11], was pointed out by Gloeckler et al. [12] and led to numerous follow-up work. Gloeckler et al. [13] extended their spectral description with an exponential term that accounts for losses at the high energy end of the distribution due to finite space and time. They demonstrated that the lower portion exhibits a constant $v^{-5}$ slope. Desai et al. [14] and Dayeh et al. [15] investigated systematically the composition of the suprathermal population and the spectra of heavier species. They found a distinct variation with the solar cycle, or the occurrence of impulsive events, and a substantial variability of the spectra of heavy ion species in that population.

Two different types of models have been developed to explain the observed characteristics of the suprathermal tail populations, either through continuous local acceleration in undisturbed SW or as remnants from acceleration in CME and stream interaction related compressions or shocks. The widely promoted constancy of the power law portion of the suprathermal tail spectra and their presence during quiet times has inspired models of continuous local acceleration. Compressional turbulence in the SW [11, 16, 17] is suggested to provide naturally a $v^{-5}$ spectrum. But Jokipii & Lee [18] pointed to several weaknesses in the derivation of this model. Wave particle interaction [19] and stochastic acceleration by waves [20] leads to a spectrum close to $v^{-5}$, when adiabatic cooling is included. Also, reconnection in stochastically distributed magnetic islands in the SW leads to acceleration into a power law, whose index is still Mach number dependent, but tends toward $v^{-5}$ in the outer heliosphere [21, 22] and is strongest downstream of interplanetary shocks [23]. The model by Schwadron et al. [24] is a hybrid between the two model types, as it addresses acceleration in CIRs through transit time damping, which appears to produce spectra close to a power law, with indices between -5 and -6, but it also could provide acceleration in quiet SW, just at lower fluctuation levels. Similar to this model, the ones by Fisk & Lee [25], Giacalone et al. [26], and Richardson [27] address acceleration into the suprathermal regime at CIR shocks and compressions. Acceleration at CME related shocks also produce power law spectra in the lower energy portion [28, 29], but mostly at $v^{-4}$ in the observer frame, which amounts to about $v^{-6}$ in the SW frame for ions in the suprathermal speed range, with variations according to the shock strength. While these sources can explain the variability of the heavy ion spectra and, together with contributions from impulsive flares the varying composition, Fisk & Gloeckler [17] point out that a separate continuous acceleration is needed to explain the often-observed $v^{-5}$ spectra during quiet times. However, Schwadron et al. [30] have shown that a stochastic combination of different power law, exponential, and
Gaussian spectra typically leads to a spectrum that is close to $v^{-5}$, which could equally explain the constant behavior during quiet times.

Popecki et al. [31] showed that He$^+$ tails steepen from the slow compressed wind to the fast CME related wind in CME compressions, with large intrinsic variability, which could provide a variety of source spectra for a superposition as discussed by Schwadron et al. [30]. Tessein et al. [32] have demonstrated that the fluxes of the suprathermal tails at compressions correlate with the strength of the turbulence in its immediate vicinity. These findings raise the question, whether, perhaps, the suprathermal tail fluxes decrease and their spectra vary systematically as a function of distance (and/or time) from CIR or CME related sources. In other words, could, in principle, the reservoir of suprathermal tail populations be replenished just from several, stochastically distributed, localized sources in the heliosphere?

In this contribution, we will take advantage of a previous systematic study of the evolution of the PUI velocity distribution across SW compression regions and its dependence on the strength of the compression [33] to perform a similar systematic study of suprathermal He$^+$ tail fluxes and spectra. This study should provide further information on the question whether the compressions and shocks, which are known to energize ions could be sources of these suprathermal tails or whether an additional process may be needed that operates anywhere in the SW. In Section 2 we will briefly summarize the data analysis method, followed by the presentation of the results in Section 3, and a discussion of them along with their implications in Section 4. We will conclude with a summary of the results, conclusions, and an outlook toward future investigations.

This paper is in tribute of Dr. Ed Stone on his 80th birthday, whose leadership of the ACE [34] and Voyager Interstellar Mission [35] has contributed substantially to the studies of suprathermal tails in the heliosphere.

2. Superposed Epoch Analysis Method to Study Suprathermal He$^+$

In recent work, Bower et al. [33] have performed a superposed epoch (SPE) analysis of the behavior of the PUI cutoff across SW compression regions, from the slow compressed via the fast compressed and peak speed region all the way into the rarefaction region. They showed that the PUIs experience a maximum positive cutoff shift at the end of the fast compressed wind, with sustained positive shifts into the first half of the rarefaction region. The magnitude of this shift correlates with the mean SW speed gradient across the compression. The unexpected positive shift in the rarefaction region appears to be connected with the continuing presence of compressional fluctuations from the fast compression region well into the rarefaction region, which thus are a likely contributor to the energization of the PUIs observed through the cutoff shift. In this study, also substantial suprathermal tails were observed in the compression region, which we will follow up on here.

For the study, we use the He$^+$ count rate distributions for 2007 – 2014 from the PLASTIC instrument on STEREO A [36] binned as a function of speed and angle, transformed into the SW frame [37, 38], which facilitates the direct comparison with previous suprathermal particle spectra. In order to provide spectra of the velocity distribution function of these ions, we make use of the fact that the differential energy flux density $E\Delta J/\Delta E$ as measured by an instrument that uses an electrostatic analyzer for energy determination is directly proportional to the observed count rate in the spacecraft frame, assuming a detection efficiency that is constant over energy. Given that the species, here He$^+$, is determined by the instrument the observed energy $E$ is directly translated into the particle speed in the spacecraft frame $v'$. Because we will compare the suprathermal tail fluxes directly with the concurrent PUI fluxes (the expected source population) there is no need to obtain absolute fluxes, and thus only a correction for the energy dependence of the PLASTIC He$^+$ detection efficiency is applied here to the observed count rates.
To obtain this efficiency, the ratios of single and coincidence rates in the SW main channel of the PLASTIC time-of-flight system are used, at an energy just below the He$^+$ cut-off energy. Thus, the variation of the He$^+$ cut-off with solar wind speed provides the energy dependence of the He$^+$ efficiency. For the PLASTIC calibration to He$^+$ and a direct comparison with ACE SWICS see also Möbius et al. [39]. Furthermore, $E\Delta J/\Delta E = v^4 f/2$, where $f$ is the velocity distribution function and $m$ the mass of the observed species. Because we are using solely observations in the SW section of PLASTIC, we take $v' = v + V_{sw}$, where $v$ is the He$^+$ speed in the SW frame and compute $f$ from the observed efficiency corrected count rate.

Let us briefly review the method used in the SPE analysis here, which is described in more detail elsewhere [33]. After applying a sliding average, the compression regions are identified by maxima in the SW density that coincide with SW speed increases. The density peak is taken as the stream interface, or the boundary between slow and fast compressed SW, and thus used for the epoch of the time scale. From here, the start of the slow compressed wind is identified by the preceding minimum of the SW speed, the end of the fast compressed wind/start of the peak region by the maximum of the speed gradient, and the end of the peak region/start of the rarefaction by the maximum of the SW speed. The rarefaction region ends when another speed minimum is encountered. To synchronize the individual compressions for the superposition, the average length of each of these regions is computed and then used as the time scale for the combined data. For each of the individual compressions, the length of each region is compressed or stretched accordingly.

Figure 1 shows the superposition of the strongest 25% of the compression regions during the observation period, with each region highlighted by a specific color, whose scheme will be maintained in the Figures presented below: slow compressed wind (red), fast compressed wind (purple), peak region (white), and rarefaction region (blue), which is subdivided into four equal consecutive time intervals to follow the evolution of the tail spectra. Shown are from top to bottom: SW speed $V_{sw}$ (blue) and density $n_{sw}$ (red) (panel a), magnetic field strength $B$ (panel b), tail count rate for $w \geq 1.6$, normalized to the maximum PUI count rate, with no quiet time criterion (panel c), with a threshold of the STEREO SIT.
$^4$He fluxes (panel d), with a threshold of the PLASTIC tail count rate (panel e), absolute strength of the SW speed fluctuations $|\delta V_{sw}/\delta t|$ (panel f), and average local SW speed gradient $\delta V_{sw}/dt$ (panel g).

In all cases the start of the suprathermal tail is defined at $v/V_{sw} \geq 1.6$ in the SW frame. We use a somewhat larger value than Gloeckler et al. [12], who used 2.39 in the spacecraft frame, because the cutoff is varying substantially with ecliptic longitude due to the interstellar gas flow velocity pattern at 1 AU which produces a modulation by about 15% between downwind and upwind [40]. To obtain the unbiased evolution of the tail fluxes across the compression regions we first show the normalized tail distributions as observed, without quiet time criterion, in panel c. Then we apply two different criteria to select quiet times, whose importance may become clear when discussing the results. In panel d, we select from the original dataset, only those 5-minute time intervals, for which the concurrent $^4$He flux at 0.16-0.24 MeV/nuc, measured with STEREO SIT is $<0.5$ (cm$^2$ sr s MeV/nuc)$^{-1}$. In panel e, we apply a criterion in analogy to the one used by Fisk & Gloeckler [11], who required $\leq 1$ H$^+$ count/4h for $w' > 2.39$ (in the spacecraft frame) in the Ulysses SWICS data. Because of the larger PLASTIC geometric factor, we select only those 1-hour PLASTIC data time intervals, which contain $\leq 1$ He$^+$ counts for $w \geq 1.6$. It should be noted that Dayeh et al. [15] applied a similar criterion for their quiet time selection, although defining their absolute threshold based on the fraction of time intervals with the lowest fluxes in the complete flux distribution over the observation time. We keep a fixed count rate selection for now. After introducing these data selection schemes for the total tail count rates relative to the maximum PUI count as a function of time across the superposed compression in Figure 1, we use them also to construct spectra of tail distributions, separately for each regional subdivision.

3. Analysis Results

Figure 1 shows the evolution of the superposed compression in the same way as used in [33] for the bulk PUI evolution. In fact, panels a, b, and f show the same quantities, yet for a slightly different selection of compressions. For context, panel g is added to show the average local SW speed gradient. As can be seen from panels c and d, with the unbiased tail counts and selected quiet times from the SIT $^4$He fluxes, the normalized tail count rate shows two distinct maxima in the slow and fast compressed wind, followed by another maximum after the end of the rarefaction region, probably indicating the arrival of the next compression. Based on this temporal evolution of the normalized tail count rate, it is obvious that the rate systematically decreases with distance from the compression, but it increases again toward the end of the rarefaction region, when apparently the next compression arrives. This behavior is very similar in panel c and d. In contrast, the normalized tail count rate is much reduced through the entire time interval, after the quiet time count rate threshold criterion has been applied using the observed PLASTIC He$^+$ tail count rate. Also, except for statistical fluctuations, the normalized count rate remains almost constant throughout.

Next, we evaluate the normalized tail distribution spectra as a function of the normalized speed $w = V/V_{sw}$ in the SW frame across the different regions, starting with the compression itself. Figure 2 shows the spectra in a log-log representation for the slow compressed (red), fast compressed (purple), and peak speed (black) regions for three ranges of increasing average SW speed gradients across the combined slow and fast compressed SW from the left to the right (at the bottom of each panel). Error bars represent the statistical uncertainties and are mostly smaller than the symbols, except for the highest energies. Also shown are Chi-squared fit lines, assuming a power law, with resulting indices and fit errors shown in the upper right corner of each panel. Spectral indices between about -5.2 and -8.2 are found, a range that is consistent with the findings by Popecki et al. [31] for two sample compressions and shocks. Generally, the spectra are harder in the slow compressed SW than in the other two regions. They appear to soften systematically from the smallest to the largest average speed gradients. That the spectra appear to extend further in the slow compressed SW is due to the upper PLASTIC energy limit of 80 keV/q. For higher SW speed the observations extend to lower values in $w$. 


Figure 2: Spectra of suprathermal tails, without any quiet time condition imposed, in the slow compressed SW (red), fast compressed SW (blue), and peak SW (black) for three different ranges in the strength of the SW speed gradient across superposed compression regions, both slow and fast compressed SW combined.

In Figure 3 we turn to the normalized tail distribution spectra in each of the four consecutive sections of the rarefaction region for the largest speed gradient range from Figure 2. The four sections are marked with different symbols and shades of blue. Here, we compare the results for different quiet time selections, unbiased samples (left), only time intervals with ≤0.5 (cm$^2$ s MeV/nuc)$^{-1}$ of $^4$He at 0.16-0.24 MeV/nuc in SIT selected (center), and only time intervals with ≤1 count/h He$^-$ for $w \geq 1.6$ in PLASTIC selected (right), for the range with the largest solar SW gradients from Figure 2. For all cases, the power law indices range from -6.2 to -9.0. For the unbiased selection and the quiet time selection that uses STEREO SIT data, the normalized count rates start highest (with ≈0.01 at the lowest speed) in section

Figure 3. Spectra of suprathermal tails in four consecutive sections (R1, 2, 3, and 4) of the rarefaction region based a superposed epoch sample of compression regions for the strongest SW speed gradients. Left: Unbiased sample, with no quiet time criterion applied

Center: Only time intervals with ≤0.5 (cm$^2$ s MeV/nuc)$^{-1}$ of $^4$He at 0.16-0.24 MeV/nuc in SIT selected

Right: Only time intervals with ≤1 count/h He$^-$ for $w \geq 1.6$ in PLASTIC selected

R1, then decrease by about a factor of 3 to R2 and R3, and increase to about the same level again in R4, thus mimicking the behavior of the total normalized tail fluxes in Figure 1. There is no visible difference between these two selections in the power law indices. In contrast, the spectra in all four sections appear to be almost identical at approximately the level of R2 and R3 from the previous selections when using PLASTIC tail count data for the quiet time criterion. The spectral indices are similar to those in the left two panels, perhaps, with slightly softer spectra though.
4. Discussion

Let us start the discussion with the regions that appear to feature most prominently suprathermal tails, i.e. the slow and fast compression as well as the peak speed region. Here, the total tail fluxes peak separately in both regions, and the spectra appear harder in slow wind than in the fast wind, similar to findings in [31]. Also, the spectra appear to harden for smaller SW speed gradients, which seems counterintuitive at first glance. On the other hand, the tail count rate at the low speed end of the spectra increases as a function of the speed gradient. Apparently, a steeper gradient, indicative of a stronger compression, may produce a higher tail flux, but it appears as if the acceleration to higher energies is less effective. The situation looks similar for the steeper (and thus softer) spectra in the fast-compressed and peak wind compared to the slow-compressed wind. At this point this is not understood and may only be addressed quantitatively in a combined simulation and data analysis. A marked dip between the two maxima is also visible, when inspecting the time evolution of the total tail count rate (not shown here), but it is probably enhanced when choosing the normalized tail count rate. As shown in [33], the total PUI count rate peaks near the boundary between slow- and fast-compressed wind, thus suppressing the normalized tail count rate here. Overall, the normalized tail count rates do not follow closely the speed gradient, nor the fluctuation level, although they are generally high where these two indicators are high.

There are small, but visible differences between the time evolution of the unbiased normalized tail count rates and those selected for quiet times using STEREO SIT \(^3\)He. The latter probably indicate where times with higher energy particles have been eliminated from the slow- and fast-compressed wind, as expected for such a selection. However, the evolution in the rarefaction region is largely unchanged. For the \(^3\)He tail count based quiet time selection analogous to the one used by Fisk & Gloeckler [11] and similar to Dayeh et al. [15], the temporal evolution is starkly different. Here, any visible temporal evolution over the superposed compression is removed, and the count rates reflect tail fluxes close to the lowest levels in the center of the rarefaction region, but with large, most likely purely statistical, variations. When integrated over the time intervals into spectra, this behavior is reinforced. All spectra in the rarefaction region taken with all three criteria show power law indices that vary visibly around values steeper than -5, values and variations similar to those found by Popecki et al. [31]. While the unbiased and SIT related selections reflect the systematic tail flux decrease toward the center of the rarefaction region (note, the tails increase toward the preceding and the following compression), all spectra contain similarly low fluxes for the selection with a threshold for the PLASTIC tail counts. It is also very surprising that apparently even during the compression itself quiet time intervals seem to be selected, with normalized tail count rates similar to those in the rarefaction region.

How can such a surprising result, at first sight, be understood? To make progress with this question, let us emphasize that with the latter quiet time criterion data time intervals are selected and accumulated that either contain one or no count, individually. Of course, accumulated over a large portion of a multi-year data set collectively they still generate meaningful count rates and spectra. Barring any systematic effects, individual counts, as selected here, are distributed between the time intervals that are accumulated according to a Poisson distribution. With a threshold of \(\leq 1\) count/h, therefore, all those time intervals are selected for accumulation that contain 0 or 1 count for any mean count rate that prevails during the observation period of interest. Figure 4 shows the fraction of time intervals (or data) that are selected with this criterion from Poisson distributions for mean count rates ranging from

![Figure 4](image-url)

**Figure 4:** Fraction of selected data time periods as a function of mean count rate for a threshold of \(\leq 1\) Cts/h, if the events are Poisson distributed.
0 to 10 counts/h. Even for 9 counts/h, 0.001 of the time intervals fulfill the selection criterion.

It becomes immediately clear that fluxes over quite a range in magnitude contribute to the accumulated population, thus even allowing tails in the compressions to contribute, if no further condition is applied. In other words, the underlying fluxes of the observed population must have a substantial uncertainty. Secondly, due to the required threshold only a constant count rate of ≈1 count/h is returned.

With this explanation in mind, the unbiased tail count selection and the one screened for energetic $^4$He fluxes with STEREO SIT appear to provide a realistic temporal evolution across the superposed compression region. Both indicate in the total normalized tail fluxes and the spectra a well visible gradient from the preceding and following compression into the rarefaction region. This observation appears consistent with the compressions being a source for the tails here. The spectra in the rarefaction region appear to be closer to the ones from the fast-compressed wind and peak regions. Why the harder spectra of the slow compressed wind don’t seem to show up more prominently here is not understood and should be studied further in the future. Furthermore, the quiet time criteria used previously appear to produce a stochastic superposition of particles from regions with a variety of mean fluxes, which may have different power law indices from -5 as found here. A stochastic superposition would be consistent with the prediction by Schwadron et al. [30] that a composite spectrum with about $n^{-5}$ results in this scenario.

While quiet time selections based on a threshold in the observed total tail count rate have intrinsic value, when analyzing average spectral [12, 13] and compositional [14, 15] characteristics of suprathermal tails, one needs to be aware of potential shortcomings of this method when attempting to extract spatial and temporal evolutions, even with an SPE method as used here. Firstly, such a threshold selects particles from a rather wide range of mean fluxes, as an intrinsic property of the Poissonian distribution of the particles. Secondly, any temporal evolution that may point to potential localized sources is eliminated.

5. Conclusions and Outlook
Building on a related SPE analysis of the properties of the bulk PUIs across SW compressions [33], we have performed the first systematic study of the evolution of the total normalized suprathermal tail count rates as a function of average temporal separation from the stream interface. We found the strongest tails in the slow-compressed, fast-compressed, and peak speed wind regions, largely consistent with the findings by Tessein et al. [32], with a harder spectrum in the slow wind than in the other two regions, consistent with the findings by Popecki et al. [31]. The spectra in the compression region tend to soften for steeper average SW speed gradients. The total normalized tail count rates and the levels of the spectra decrease in the rarefaction region as a function of distance from the preceding and following compression, with a minimum in the center of the rarefaction. However, a constant low tail flux is returned when applying a quiet time selection with a threshold in the observed PLASTIC He+ tail count rates, which is explained with the intrinsic behavior of Poisson distributed tail counts for such low count rates. The distinct temporal variation of the tail count rates across the compression region is found for the unbiased data and for a selection of quiet times using SIT $^4$He fluxes, which appears consistent with a source of the tails in the compressions, and per extension near shocks of the interaction region. A $n^{-5}$ tail spectrum may then emerge as a stochastic superposition of these sources, as predicted by Schwadron et al. [30].

To assess this emergent hypothesis quantitatively, a combination of simulations of the acceleration of ions into the suprathermal tails and their transport to the observer together with a detailed data analysis for the parameter dependencies found in the simulations will have to be undertaken. This extension of the current pilot study is planned for the near future.

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