Suprathermal Ions in the Outer Heliosphere

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Abstract

Suprathermal ions form from interstellar gas that is first ionized into pickup ions and then accelerated to tens and hundreds of keV in energy. The resulting suprathermal ion spectra with hundreds of keV have been previously observed throughout the heliosphere; however, measurements at lower energies, around the pickup ion cutoff energy where they are accelerated from, were limited to <10 au. Here we present a statistical study of suprathermal ions in the keV to hundred keV energy range. We use the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument on the New Horizons spacecraft, which recorded observations at a wide range of heliocentric distances, and compare these measurements to charge energy mass spectrometer (CHEMS) observations on Cassini, which cruised to and remained at Saturn. We find that the power-law exponents of suprathermal ion intensity over energy are between −1 and −2, change abruptly close to discontinuities that are likely corotating merged interaction regions, and show a long-term evolution on the timescale of the solar cycle. The independent measurements from New Horizons and Cassini are consistent, confirming the first fully calibrated measurements from the New Horizons/PEPSSI instrument.

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

1. Introduction

Interstellar gas that approaches the Sun is ionized and accelerated by the convective electric field to solar wind speeds, yielding interstellar pickup ions. These ions move with the solar wind bulk speed when averaged over a gyro orbit. Their instantaneous speed as they gyrate varies from zero to two times the solar wind speed, which is why their distribution function shows a cutoff at twice the bulk speed in the rest frame.

The ions are then further accelerated to higher energies, forming a population referred to as suprathermal. It shows energy distributions that can be approximated by power laws \( j \propto E^{-\gamma} \) (with the differential intensity \( j \) and the kinetic energy \( E \)). The suprathermal exponent has been observed inward of 10 au to be \( \gamma \approx -1.5 \) above the keV range (Gloeckler & Geiss 1998; Denker et al. 2007; Hill & Hamilton 2010; Fisk & Gloeckler 2012; Mason & Gloeckler 2012) and of a similar value at hundreds of keV in the heliosheath (Decker et al. 2005; Krimigis et al. 2013; Fisk & Gloeckler 2014).

The nature of the acceleration process is still under debate and there are a variety of theories, such as, for example, adiabatic compression within and diffusion out of shocks (Fisk & Gloeckler 2012), reflection in contracting and reconnecting magnetic islands (Drake et al. 2013), damping of MHD waves (Le Roux & Ptuskin 1998), the structured Coulomb forces in a sparsely populated plasma (Randol & Christian 2014), or reflection off electrostatic cross shock potentials (Zank et al. 1996). All of these processes lead to exponents of \( \gamma \approx -1.5 \).

Diffusive shock acceleration in the interplanetary medium is also a possibility but produces a range of exponents (Section 4.1). Strong shocks with large changes in the solar wind speed yield hard spectra. For example, a factor 4 compression yields \( \gamma = -1 \) if the shock is planar (Lee et al. 2012). Weaker shocks yield softer spectra that fall more steeply. Compressions that are not accompanied by shocks yield similar spectra (Giacalone et al. 2002; Jokipii & Giacalone 2007).

Power laws can be interpreted as approximations to the kappa distribution that naturally arises (Livadiotis & McComas 2009) from the Tsallis statistical entropy (Milovanov & Zelenyi 2000; Tsallis 2009), similar to the Maxwellian distribution that results from the Boltzmann statistical entropy. Maxwellian distributions (found in thermal equilibrium) are included in this formalism (\( \gamma \rightarrow -\infty \)). Systems that are far from equilibrium will have larger exponents (Livadiotis & McComas 2010, 2011). The largest exponent of an ideal kappa distribution with a suprathermal power law extending to infinite energies is \( \gamma = -1.5 \), beyond which such a distribution cannot be
normalized because the density would be infinite. In reality $\gamma > -1.5$ can exist if the power law is breaking down at high energies. However, such a breakdown is not covered by the Tsallis entropy formalism.

Whatever accelerates the pickup ions, the mechanism does break down in the hundreds of keV energy range and leads to a spectral break, meaning that the power-law exponent at these higher energies is steeper (Gloeckler & Geiss 1998; Fisk & Gloeckler 2012).

In this paper we present the pickup and suprathermal ion spectra outbound of 5 au and at energies around the pickup ion cutoff at a few keV nuc$^{-1}$ using New Horizons and Cassini. There has been an observational gap because other measurements were either at smaller distances to the Sun (Denker et al. 2007; Fisk & Gloeckler 2014), or at lower (Randol et al. 2013; Zirnstein et al. 2018) or higher energies (Krimigis et al. 2013).

As is typical for a single spacecraft measurement, changes in the ion environment of New Horizons cannot be discerned as a result of New Horizons’ increasing distance to the Sun (data used from 5 to 40 au) or as a result of the solar cycle or other time dependence (2007–2018). We therefore add a second spacecraft and compare the New Horizons results to measurements taken with the Cassini spacecraft, which only had a small change in distance to the Sun (data used from 5 to 10 au) compared to New Horizons.

This is the first time that fully calibrated measurements of the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument are presented. Specifically, we compile the results of several laboratory and in-flight calibration efforts. Comparison between results from New Horizons and Cassini offers an additional validation for this new PEPSSI calibration.

2. Data Set

2.1. New Horizons/PEPSSI

The New Horizons spacecraft launched in 2006 with the prime objective of studying Pluto and its system of moons (Young et al. 2008). This objective was broadened for its extended mission to include heliospheric and Kuiper Belt science, including a flyby of the Kuiper Belt Object 486958 2014 MU$\text{}_{\text{60}}$ (Stern et al. 2018). The first measurements with the PEPSSI instrument (McNutt et al. 2008) were taken around Jupiter at 5 au (McNutt et al. 2007; Haggerty et al. 2009; Hill et al. 2009a; Kollmann et al. 2014). From 2012 on, at 20 au, PEPSSI was taking measurements almost continuously, including at Pluto (Bagenal et al. 2016), and is now at 43 au, where it flew by the Kuiper Belt Object MU$\text{}_{\text{60}}$.

We use a new calibration, based on measurements with the PEPSSI engineering model (EM), that has been scaled to efficiencies measured in-flight (Appendix A). The instrument nominally detects and distinguishes tens to hundreds of keV ions and electrons but is also capable of measuring Galactic Cosmic Rays (Hill et al. 2018). For hundreds of keV particles, PEPSSI measures the energy deposited in solid state detectors (SSDs). Our study will focus on lower-energy measurements that rely solely on the time of flight (TOF) measurements.

PEPSSI measures the TOF of ions between “Start” and “Stop” foils. Secondary electrons are produced in these foils and are detected by the start and stop anodes of a microchannel plate (MCP). PEPSSI is able to measure ions down to the few keV nuc$^{-1}$ range because it has relatively thin foils compared to other versions of the instrument (Clark et al. 2016) and because a $-2.63$ kV potential relative to space accelerates ions before hitting the first foil. A TOF measurement alone is not able to distinguish ion species. The different energy losses of ion species indicate that the instrument raw count rate around the pickup ion cutoff is dominated by pickup He$^+$ (Appendix A). We assume in the following that this also applies to other energies and will only show figures and results calibrated for He$^+$. Given that in this manuscript we will study relative changes in the time and energy of the ion intensities and the distribution functions of different suprathermal ion species are relatively similar in shape (Gloeckler et al. 2008; Hill & Hamilton 2010; Mason & Gloeckler 2012), the distinction between ion species is not critical here.

PEPSSI delivers two data products: “channels,” which are count rates of all measured particles that are binned in TOF, and “event data,” which include a subset of particles, where the precise TOF is reported. We use the event data in order to get spectra of high-energy resolution and scale these so that their amplitude matches the coarse spectra from the channelized data. We split the measurements into intervals of 0.02 yr length. For each interval we determine spectra at up to eight different solar wind speeds that were determined independently (Elliott et al. 2016, 2018) by the Solar Wind Around Pluto (SWAP) instrument (McComas et al. 2008). This approach prevents us from mixing measurements during different solar wind conditions, particularly before and after shocks that might occur in each interval. To make spectra measured during different solar wind bulk speeds more easily comparable, we shift all spectra to solar wind speeds of 500 km s$^{-1}$ (unless stated otherwise) while conserving the phase space density.

We transform the measurements from the spacecraft frame (SF) to the solar wind frame (WF). To do this, we convert the calibrated intensities $j_{\text{SF}}$ (particles per time, area, solid angle, and energy interval) into phase space densities $f$ (particles per volume in real and velocity space) as a function of ion velocity $v_{\text{WF}}$ in the spacecraft frame:

$$f = \frac{m}{v_{\text{WF}}} j_{\text{SF}}. \quad (1)$$

We then calculate the ion velocities $v_{\text{WF}}$ in the frame that moves along the wind’s bulk (WB) velocity $v_{\text{WB}}$ of the solar wind based on the law of cosines:

$$v_{\text{WF}} = \sqrt{v_{\text{SF}}^2 + v_{\text{WB}}^2 - 2v_{\text{SF}}v_{\text{WB}}\cos(\alpha_{\text{SF}})}. \quad (2)$$

Bulk speeds are currently available until 2016 (Elliott & Mukherjee 2017). $\alpha_{\text{SF}}$ is the angle between the ion velocity in the spacecraft frame and the bulk flow direction that is assumed as radial. Equation (2) neglects the speed of the spacecraft because it is well below the solar wind bulk speed. Because $f$ is conserved, we can now calculate the intensities $j_{\text{WF}}$ in the solar wind frame:

$$j_{\text{WF}} = \frac{f v_{\text{WF}}^2}{m}. \quad (3)$$

PEPSSI has six sectors pointing in different directions (labeled S0–S5). The efficiencies between the sectors differ by two orders of magnitude so that we can assume that most counts are coming from S0, the direction of the most efficient sector. This approach avoids ambiguity that results from electronic cross talk between the sectors. New Horizons is spinning most of the time during which sector S0 has an angle of $\alpha_{\text{SF}} = 35^\circ$ relative to the Sun direction. We currently only use data taken within $10^\circ$ to this nominal orientation.
Frame conversion based on a single angle $\alpha_{\text{SF}}$ will yield different angles $\alpha_{\text{WF}}$ in the solar wind frame, depending on energy. It is still fair to compare intensities at different $\alpha_{\text{WF}}$ angles, as the pickup and suprathermal ion distribution is often found to be consistent with being isotropic (see the right panel of Figure 1, discussed below, and Gloeckler et al. 1997; Randol et al. 2012) and observed anisotropies are small (Möbius et al. 1998; Zhang 2005), consistent with the expectation of sufficiently strong scattering (Vasyliunas & Siscoe 1976), which can result from Alfvénic fluctuations due to stream shear, shocks, or the pickup process (Zank 1999; Zank et al. 2018).

Sample spectra of suprathermal ions measured by PEPSSI that were converted to the solar wind frame are shown in the left panel of Figure 1.

### 2.2. Cassini/CHEMS

The Cassini spacecraft launched in 1997 with the objectives of studying Saturn, its magnetosphere, rings, and moons, particularly the moon Titan (Matson et al. 2002). In this study we mostly use Cassini data from the cruise phase, spanning from the Jovian encounter until orbital insertion at Saturn (2001–2004), when the data format was the same as that during the orbit around Saturn. After Cassini went into orbit, we only use a few intervals when Cassini was well outside of the Saturn’s bow shock. Until 2012, while the Cassini plasma instrument Cassini Plasma Spectrometer (CAPS; Young et al. 2004) was operating, we use combined ion and electron plasma data and magnetic field measurements to identify boundaries (Delamere et al. 2013, 2015). After this, we only use times where Cassini was more than 10 Saturn radii away from the nominal bow shock location (Masters et al. 2008). In order to simplify data processing, we limit ourselves to times where the spacecraft was not spinning.

The suprathermal He$^+$ ion measurements we use here are from the Magnetosphere Imaging Instrument/Charge-Energy-Mass-Spectrometer (MIMI/CHEMS) instrument (Krimigis et al. 2004). CHEMS measures ions in the tens to hundreds of keV energy range and distinguishes them by measuring their $E/q$ in an electrostatic analyzer (with $q$ being the charge), their TOF, and deposited energy. The channelized CHEMS data are scaled with filtered event data in order to suppress background (Vandegeiff et al. 2013).

Solar wind speeds are determined through CHEMS by determining the pickup ion cutoff (Appendix B). We convert the measurements into the solar wind frame (Section 2.1) using the directional information provided by the 3 sectors of CHEMS. We extend the directional coverage by combining times of different spacecraft attitude. We select CHEMS data with $0 \leq \alpha_{\text{WF}} \leq 30^\circ$ between the ion velocity in the solar wind frame and the bulk flow direction unless stated otherwise. This selection is without loss of generality because the pickup and suprathermal distribution are approximately isotropic in the solar wind frame (Section 2.1).

After transformation to the wind frame, we bin the data over 0.03 yr. In order to not mix measurements at different solar wind speeds, we scale all ion speeds relative to the current solar wind bulk speed before binning. Instead of analyzing and fitting the data as a function of normalized speed, we shift the spectra data assuming, without loss of generality, that the solar wind speed is $500 \text{ km s}^{-1}$, unless stated otherwise. The right panel of Figure 1 shows example spectra, measured at different angles relative to the Sun direction. It can be seen that the distribution is indeed roughly isotropic, as expected (Section 2.1).

Because we average measurements at different times and directions together, we cannot resolve small anisotropies. The apparent anisotropy in Figure 1 changes its appearance depending on the details of the binning and shows no continuous trends over direction or energy. This suggests that the anisotropy is an artifact of how we are constructing the spectra. Measured suprathermal ion intensities can be a factor 2 higher or lower compared to a fit (not shown) over all data. Any kind of real anisotropy needs to be within this envelope.

### 3. Observations

#### 3.1. Long-term Dependence

We fit the suprathermal ion distributions from above the pickup ion cutoff ($\approx 10 \text{ keV}$) to $\approx 100 \text{ keV}$ with power laws.
following $j \propto E^{\gamma}$. Figure 2 shows different values of $\gamma$, sunspot number, and heliocentric distance as a function of time. The exponent varies around $\gamma \approx -1.5$, as predicted by various theories (Section 1), but is usually not equal to this value nor is $-1.5$ an upper or lower limit. Measurements taken at the time where New Horizons and Cassini were at the same heliocentric distance have similar exponents.

It can be seen that the hardest spectra ($\gamma \approx -1$) are found at $\approx 2001$ and $\approx 2014$, close to solar maxima, and at $\approx 2006$, before solar minimum. The softest spectra are found in-between.

3.2. Correlation with Bulk Speed

There is a large temporal variability in the suprathermal ion spectra at $> 5$ au. Because all spectra used have sufficient count rates and are fit well with power laws, we interpret this variability as true variations, not as a signature of uncertainties in the determination of the exponent.

The described scatter in the suprathermal exponent measured by New Horizons correlates with the solar wind bulk speed, as shown in Figure 3. The Cassini data that were measured closer to the Sun do not show a clear exponent-speed correlation, which we will discuss in Section 4.3.

3.3. Role of Corotating Interaction Regions

In order to interpret the exponent-speed correlation, we study shock-like discontinuities because their observations are accompanied with both changes in wind speed and in the spectral parameters. We select discontinuities that show abrupt increases both in the PEPSSI intensities at fixed energies and in the SWAP solar wind speed (Figure 4).

The discontinuities are likely signatures of corotating interaction regions (CIRs) or their successors, like merged interaction regions or corotating pressure enhancements (Gazis et al. 1999; Gazis 2000). This is because the intervals between discontinuities are consistent with occurring every or every few solar rotations and because they are found in the declining phase of the solar cycle (Gosling et al. 1995). It is possible that the interaction regions are accompanied by shocks, even though Mach numbers decrease (Zank & Pauls 1997) and shocks were observed to erode with distance to the Sun (Burlaga 1983). Because New Horizons lacks a magnetometer, a definitive confirmation for the discontinuities being shocks is not possible. Also, given that simple compressions (Giacalone et al. 2002) are capable of accelerating particles and even remnant shocks are accompanied by at least a fraction of the particles they were accelerating (Rice et al. 2000), a clear shock identification is not critical for a first analysis.

The two example spectra shown in the left panel of Figure 1 are typical observations before and after a discontinuity. After a discontinuity, the intensity increases more for the low-energy suprathermal ions, consistent with an acceleration just across the pickup ion cutoff energy. Because the immediate acceleration only reaches tens of keV while the population at higher energies is slightly more affected, the spectrum becomes softer after acceleration ($\gamma \approx -2$). Note that this change in exponents...
is opposite to the intuitive expectation of acceleration yielding harder spectra. The observed behavior of He$^+$ ions is consistent with what has been observed for H$^+$ pickup ions (Gloeckler et al. 1995; Zirnstein et al. 2018).

The suprathermal exponent before the discontinuity is typically $\gamma \approx -1.6$. At the discontinuity, it abruptly decreases to $\gamma \approx -1.8$ and then recovers toward the initial value (Figure 5). This behavior is similar to 1 au in the sense that the spectra are softest at the discontinuity. At 1 au the gradual change in exponent occurs before the discontinuity (Fisk & Gloeckler 2012), not afterward, as we observe it at $\approx 30$ au.

Based on the observed time profile of the discontinuity we calculate average suprathermal exponents 1–10 days before and 0.5–2.5 days after the discontinuity. We overplot the resulting pairs of $\gamma$ in Figures 2 and 3. It can be seen that changes around discontinuities are well aligned with the other data that were not selected for discontinuities and cover a similar range of exponent values. The similarities in the filtered and unfiltered correlation (Figure 3), as well as the similarity between the time profiles (Figure 4), suggest that CIRs play an important role in determining the value of the exponent.

Cassini data do not show such a clear correlation, even when we only consider active times of high and/or variable intensities (Hill et al. 2009b; Hill & Hamilton 2010). The absence of a correlation might be because the observation period did not show clear CIRs (Section 4.2).

4. Discussion

4.1. Main Acceleration

We observe suprathermal He$^+$ power-law exponents of $\gamma \approx -1.5$. This is consistent with various theories predicting such exponents (Section 1).

A theory that predicts not one but a range of exponents is diffusive shock acceleration. Where the exponent scales with the compression ratio $X$ between downstream and upstream bulk speeds relative to the shock (Lee et al. 2012) following

$$\gamma = \frac{-X + 2}{2X - 2}. \quad (4)$$

The speeds observed at New Horizons (Elliott & Mukherjee 2017) are in the range 340–440 km s$^{-1}$, equivalent to a maximum possible compression ratio of $X = 1.3$ that would only yield very soft spectra with $\gamma = -5.6$. However, suprathermal particles accelerated in a shock stay close to the shock or its remnant (Rice et al. 2000; Decker et al. 2001). It is therefore possible that the diffusive shock acceleration responsible for the observed exponents occurred closer to the Sun. For example, wind speeds from Advanced Composition Explorer/Solar Wind Ion Composition Spectrometer (ACE/SWICS, Gloeckler & Geiss 1998) at 1 au are in the range 280–700 km s$^{-1}$ (Gilbert et al. 2018). The maximum possible compression ratio is therefore $\gamma = -1.5$, meaning that
diffusive shock acceleration cannot be ruled out based on the observed hard spectra.

4.2. Subsequent Cooling

The exponents observed at >5 au vary roughly from −2 to −1. This is a small range compared to 1 au, where exponents from −3 to −1 are observed (Fisk & Gloeckler 2012). Even though relatively small, the systematic behavior of the exponent changes we observe here reveal information on the underlying physics.

The finding that high speeds correlate with soft spectra (with high intensities near the pickup ion cutoff) suggests that the speed value, not how it was reached, is determining the exponent. Whatever process is responsible for accelerating across the pickup ion cutoff therefore works more efficiently (indicated through softer spectra) on higher pickup ion energies (as is the case during high solar wind speeds).

Another way of interpreting the speed correlation is that the speed itself is not important, but measures the distance along a magnetic field line to a neighboring CIR: CIRs are followed by extended rarefaction regions in which the solar wind speed decreases. At tens of astronomical units, CIRs and their successors encompass the Sun (Burlaga 1983) and a spacecraft will spend most of its time in rarefaction regions. The local solar wind speed is therefore a measure for the distance to a neighboring CIR.

CIRs leak suprathermal particles along magnetic field lines (Roelof et al. 1995) so that CIR signatures can be detected remotely from locations inward of the CIR, with lower-energy particles loosing substantially more energy than higher-energy ones (Roelof 2000). Particles are cooled while moving away from the CIR. The energy loss per time, \( \frac{dE}{dt} \), can be described through the guiding center approximation as (Northrop 1963)

\[
\frac{dE}{dt} = q \frac{dR}{dt} \cdot \epsilon + \mu \frac{dB}{dt},
\]

where \( E \), \( q \), and \( \mu \) are the particle kinetic energy, charge, and magnetic moment, \( \epsilon \) and \( B \) are the solar wind electric and magnetic fields, \( \cdot \) indicates the scalar product, and \( \frac{dR}{dt} \) is the guiding center motion due to gradient, curvature, and \( \epsilon \times B \) drift. When assuming a near-azimuthal magnetic field, a frozen-in electric field, a radial solar wind flow, and an isotropic distribution of particle momenta, Equation (5) simplifies in the non-relativistic case to (Kunow et al. 1999; Roelof 2000, 2015)

\[
\frac{1}{E} \frac{dE}{dt} = -\frac{4U}{3r},
\]

with the solar wind bulk speed \( U \) and the radial distance to the Sun \( r \). The cooling described here shifts phase space density spectra toward lower energies. Equation (6) implies that the relative energy change per time does not depend on any property of the particle, particularly not on its energy. Still, low-energy particles traveling from the CIR experienced a larger relative energy loss when reaching the spacecraft because they need more time to arrive. Longer cooling leads to a larger relative energy loss. The different energy losses stretch the spectrum, making it flatter/harder the larger the distance from the shock is. Larger distances are indicated through increasingly small solar wind speeds, therefore explaining the relation between speed and exponent.

The observations qualitatively fit the expected behavior of the exponent after the passage of the CIR discontinuity. In most cases the spectra recover right away toward their initially hard shape. This is consistent with New Horizons cutting through near-azimuthal field lines, which map quickly to locations with large azimuthal distances to the spacecraft. There are other cases where the spectra change less after the disturbance, which can be explained with more radial fields that keep mapping to a location on the CIR that is close to the spacecraft.

Most time series in Figure 5 show that the exponents after CIRs recover to values similar to before the CIR (\( \gamma \approx -1.6 \)). This asymptote is inconsistent with the cooling from Equation (6) that continuously increases the exponent. We therefore suggest that the particles leaking from the CIRs mix with a background population that was not directly accelerated at the neighboring CIR. There needs to be another process responsible for their spectral shape that does not act as abrupt as a single shock but gradually accelerates particles to high energies.

4.3. Distance from the Sun

Measurements of Cassini and New Horizons taken at the same phase of the solar cycle but at different locations show a similar average suprathermal exponent. Given the large time variability in the exponents, we cannot support that there would be significant a radial dependence of the average suprathermal exponent.

However, the spread of the exponent around its average value at a given time or location appears to depend on distance to the Sun. Exponents at \( \lesssim 10 \) au measured with Cassini appear more variable than the measurements at larger distances (Figure 2) even though the Cassini exponents shown were averaged over longer times than the New Horizons measurements. The Cassini observations also do not show an exponent-speed correlation. This behavior fits the CIR-cooling theory (Section 4.2); the environment close to the Sun is less ordered because merged interaction regions with large, clear rarefaction regions only form at \( \gtrsim 20 \) au (Burlaga 1983; Gosling & Pizzo 1999), well outside the coverage of Cassini. The correlation with speed and distance to the CIR will therefore be obscured by other dynamics.

We cannot rule out that artifacts from the method used to determine the exponents also contribute to the observed scatter in the exponents. Given that the spread is larger for CHEMS than for PEPSI, this may be because we have to combine CHEMS measurements from different (though adjacent) times in order to build up the directional distribution (Section 2.2).

5. Summary

1. Suprathermal He\(^+\) ions with energies of tens of keV at 5–40 au have power-law exponents of \( j \propto E^\gamma \) with \( -1 \leq \gamma \leq -2 \).
2. The hardest spectra (\( \gamma \approx -1 \)) are found around 2001, 2006, 2014, therefore both near solar maximum and minimum. Soft spectra are found in-between (Figure 2).
3. CIRs and their successors appear to accelerate mostly ions just above the pickup ion cutoff and therefore yield soft (\( \gamma \approx -2 \)) spectra (Figure 5).
4. There is a correlation between high solar wind speeds and soft spectra at >10 au, irrespective of how the local solar wind speed was reached (Figure 3). We suggest that the observed ions were accelerated at CIRs and moved to the spacecraft along magnetic field lines, during which they were cooled (Section 4.2).

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Appendix A
PEPSII Calibration

A.1. Species Separation

The measurements presented can only use PEPSII’s TOF system because the ions studied here have energies too low to trigger PEPSII’s SSDs.

Different ion species have their pickup ion cutoff at the same speed. Measuring the TOF distribution with an ideal instrument would lead to spectra that have all similar shapes irrespective of species. However, in order to enter the instrument, ions have to pass the “Start” foil of the instrument, which then leads to the start signal for the actual TOF measurement. While passing through the foil, ions will lose a measurable amount of energy. This energy loss is species-dependent, meaning that the TOF where the pickup ion intensity breaks down is different for every species. Due to PEPSII’s detection efficiency, spectra of raw counts as a function of TOF look different from intensity spectra as a function of energy. Raw spectra have the shape of a peak (Figure 6), where its location is of the order of 100 ns. Its exact TOF depends on the ion species dominating the count rate and the solar wind bulk speed. We find that the peak location is consistent with He\(^+\) pickup ions, as explained below.

Peaks in the raw spectra are always found below \(\approx 100 \text{ ns}\) (Figure 6). The slowest solar wind observed at New Horizons is \(\approx 300 \text{ km s}^{-1}\). Pickup ions following solar wind flowing with \(300 \text{ km s}^{-1}\) will show a cutoff at 104 ns if they are He\(^+\) and at 84 ns if they are H\(^+\). In order to interpret the observed cutoff to be due to H\(^+\) ions instead of He\(^+\), the PEPSII start foils would need to be thicker by a factor of 1.7. The PEPSII start foil when actually manufactured and flown consists of layers of 48 Å aluminum, 370 Å kapton polyimide, and 43 Å aluminum. The planned and ordered values were only different by a factor of 1.2 (50, 300, 50 Å), meaning that the observed cutoff being due to protons is unrealistic.

Figure 6 shows PEPSII raw spectra for different solar wind speeds. The main feature is a peak at TOFs in the range of 80–100 ns. Its precise location shifts with solar wind speed. If we assume that only pickup He\(^+\) ions are present in space, the expected instrument response coincides with the observed peak (blue curve). Expectation and measurement deviate at shorter TOFs because the spectrum we assume to create Figure 6 does not account for suprathermal ions.

A.2. Efficiencies

Before launch, there had been only the opportunity to measure efficiencies at one energy for each relevant ion species (McNutt et al. 2008), which is insufficient for exact instrument characterization given the large energy dependence of the efficiencies. It was not possible to use the calibration from other PEPSII-like instruments (Clark et al. 2016) because none of these instruments could reach energies as low as PEPSII. Also, to ensure the health and safety of PEPSII, it is operated at high voltages below the saturation of its MCP, which means that its efficiency will be different from all similar instruments. Intercalibration with SWAP would only provide efficiencies at the lowest energies, not an energy-dependent efficiency as needed to determine the shape of the spectra discussed here.

Efficiencies for He\(^{2+}\) around 100 keV have been measured in-flight with the Am-241 alpha calibration source internal to the flight model (FM). In order to do this, the instrument has to be commanded to go into “diagnostic mode,” where all counts of the SSDs are recorded, together with information if start and/or stop signals from the TOF system were present. Because SSDs at these energies are about 100% efficient, we can use it to determine the efficiencies \(\epsilon_1\) and \(\epsilon_2\) of detecting particles passing the start and stop foil, respectively:

\[
\begin{align*}
\epsilon_1 &= \frac{N_{12}}{N_2}, \\
\epsilon_2 &= \frac{N_{12}}{N_1},
\end{align*}
\]
Figure 7. PEPSSI FM helium efficiencies. Red: the compilation of all efficiencies that is used to calibrate the measurements. Black: efficiencies of the FM in 2016. All efficiencies are scaled here to match this curve. Green: EM efficiencies determined using a degraded alpha source. Blue: EM efficiencies using a particle accelerator.

$N_1$ and $N_2$ are the numbers of particles that are detected in the SSD and provided a start or stop signal, respectively. $N_{12}$ are the particles that produce start, stop, and SSD signals. The efficiency of the TOF-only system is then

$$
\epsilon_{12} = \epsilon_1 \epsilon_2.
$$

In order to implement this calculation, we are using event data that provide the full information on a subset of counts and normalize them to the rate channel data that provide coarse information of all counts. Efficiencies measured with the FM in 2016 are shown in Figure 7.

The FM efficiencies make use of the SSD that is not available at the low energies used in this study. To determine low energy efficiencies, we used the TOF system of the PEPSSI EM. Because the count rates observed in-flight are dominated by He$^+$ at least at the lowest energies, most of this calibration work aimed to determine helium efficiencies. During our first test we used a 100 $\mu$Ci Am-241 alpha source degraded with 30 $\mu$m aluminum and placed it 24 mm away from the PEPSSI aperture. This setup produced a continuous distribution of helium ions. We measured the count rate spectrum with the EM TOF system. Comparing these count rates with count rates measured by an independent SSD that provided measurements down to lower energies than the SSDs of the PEPSSI FM allowed us to calculate efficiencies down to 20 keV.

In order to reach even lower energies, we exposed the EM to a beam with discrete energies of helium ions. The beam was provided by the 170 keV JHU/APL instrument testing facility, which includes an Air Insulated Accelerator obtained from Peabody Scientific. The count rate of the beam was monitored before and after exposure using an independent MCP with known efficiency. The relative change in beam intensity during exposure was tracked through the count rate of start-only events in PEPSSI.

The efficiency of PEPSSI is time-dependent, likely due to charging up of the foils. The PEPSSI start foil uses aluminum that forms an insulating oxide layer so that secondary electrons released by the primary ions are not quickly replenished. The resulting charging reduces the secondary electron yield and therefore the ion detection efficiency. When the PEPSSI high voltage is turned off, the charge can equilibrate and the efficiency recovers. That kind of behavior occurs in-flight on the timescale of months and is tracked and corrected in-flight thanks to the onboard calibration source. For the accelerator beam that has locally high intensities, the efficiency changes on the order of days. In the laboratory, we therefore repeatedly measured the efficiency at the same energy in order to compensate for the efficiency dependence. The blue points shown in Figure 7 are the result from about 50 single measurements that were combined to remove the time dependence.

The particle accelerator used was able to provide helium ions down to 10 keV, which is below the nominal pickup He$^+$ cutoff. Below this energy, we extrapolate the efficiencies in order to calculate the spectra used in this study (Figure 1, left panel). Calibrated spectra in space show a relatively flat plateau of pickup ions, as is expected, therefore supporting the validity of the extrapolated efficiencies.

We currently do not calibrate for particles below $\approx 2$ keV. Helium ions need to have an ambient energy of $\approx 1$ keV (before being accelerated by the potential in front of the start foil) in order to penetrate into the TOF chamber. This energy estimate is based on the average differential energy loss (Ziegler 2008). Because there is a spread in the actual energy loss, already at $\approx 2$ keV some ions start to be stopped in the foil. This number is suggested by Monte Carlo simulations using SRIM (Ziegler 2008) and GEANT-4 (Agostinelli et al. 2003). Because the results of these simulations differ from another and we do not have evidence of a breakdown in efficiency in the measured spectra, we currently discard data below $\approx 2$ keV.

Appendix B

Solar Wind Speeds at Cassini

The CAPS/IMS instrument on board the Cassini spacecraft is the best tool to determine solar wind and magnetospheric plasma speeds. However, its measurements rely on a spacecraft orientation that points the instrument into the flow direction, which happened rarely during the cruise phase. Therefore, we approximate solar wind speed using the pickup ion cutoff measured by the MIMI/CHEMS instrument. The cutoff energy is equivalent to about twice the solar wind speed when looking into the flow direction and smaller otherwise.

We limit the data to instances where the corners or center vectors of a CHEMS sector were within $\leq 30^\circ$ from the Sun, based on attitude information with 10 minute resolution. CHEMS count rate versus particle speed spectra show a peak at about the bulk solar wind speed, which is the easiest way to determine the wind speed from these measurements (Hill et al. 2012). We fit attitude-filtered, 12h-averaged, smoothed He$^+$ spectra for their peak location and remove times where no good fit is achieved. Comparison with the available CAPS data (Figure 8) shows that the solar wind bulk speed is 1.27 times the speed where the CHEMS spectra peak. The factor is determined by the (fixed) instrument efficiency and the (selected) observation angle. We use this factor to calculate solar wind speeds at all times (Hill & Hamilton 2010).
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Figure 8. Solar wind speeds determined through two instruments on board Cassini. Red: speeds from the plasma instrument CAPS/IMS designed to measure these speeds. Black: speeds from the energetic particle instrument MIMI/CHEMS where more data are available.

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