Interim Report on the Power Law Index of Interplanetary Suprathermal Ion Spectra

M.E. Hill* and D.C. Hamilton†

*Johns Hopkins Applied Physics Laboratory, Laurel, Maryland 20723, USA
†University of Maryland, College Park, Maryland 20742, USA

Abstract. There is a continuing debate about the applicability of the theory presented by Fisk and Gloeckler (FG) regarding the formation of suprathermal ion tails in phase space density vs. velocity spectra; in the solar wind frame the FG theory predicts a power law index of -5 (which is equivalent to a differential intensity vs. energy index of -1.5). There has also been uncertainty and perhaps misunderstanding regarding the extent to which such spectra are actually observed; i.e., is there really a significant preference for the -5 index? Here we report the results of an interim technique we use to analyze ~1–100 keV/nucleon interplanetary suprathermal H^+, He^+, and He^{++} spectra measured at the Cassini spacecraft by the Charge Energy Mass Spectrometer (CHEMS) instrument of the Magnetospheric Imaging Instrument (MIMI) suite during the cruise to Saturn. We analyzed 18 active periods and report a mean index in the solar wind frame of 4.9±0.4 for protons, 5.2±0.5 for He^+, and 4.7±0.2 for alpha particles. MIMI/CHEMS offers much needed independent observations of heliospheric ions in the suprathermal energy range.

Keywords: power law index of -5; power law index of -1.5; Fisk-Gloeckler; suprathermal tails; solar wind frame vs. spacecraft frame of reference; Compton-Getting transformation; anisotropy
PACS: 96.50.Ya Pickup ions; 96.50.Vg Energetic particles; 96.50.sb Composition, energy spectra and interactions; 96.50.Pw Particle acceleration; 96.50.Ci Solar wind plasma; sources of solar wind

INTRODUCTION

The spectral form of ions above the thermal solar wind plasma energy (~2-100 keV/nucleon) has been under significant theoretical and observational scrutiny recently, initiated by the theoretical and observational work of Fisk and Gloeckler (e.g., 2008 [1]). The Fisk and Gloeckler (FG) acceleration mechanism predicts that the power law index of suprathermal ion phase space densities as a function of particle velocity should be -5 in the solar wind frame (up to an energy, typically in the 10's of keV/nucleon that is controlled by local conditions). This spectral index (equivalently a -1.5 power law in differential intensity vs. energy) was reported observationally by FG to be "ubiquitous" throughout the heliosphere. There is presently no consensus on the validity of FG acceleration or on the ubiquity of the -5 spectral index. Most or all of the observational studies in the relevant energy have been conducted by FG. Other studies at higher energies [2] found significantly different spectral indices, but were usually above the suprathermal energy range. In this study we present an interim analysis of suprathermal H^+, He^+, and He^{++} spectra that were measured from 5–9 AU at the Cassini spacecraft by the Charge Energy Mass Spectrometer (CHEMS) instrument of the Magnetospheric Imaging Instrument (MIMI) suite during the 1999-2004 cruise to Saturn (e.g., Figure 1). Within measurement uncertainties the observed set of H^+ and He^+ spectra agree with the v^{-5} form (v is the ion speed in the solar wind frame), while for He^{++} the spectrum is somewhat harder than this. There are also systematic uncertainties inherent in our interim technique that we will address. We report these measurements, including the strengths and limitations of the analysis technique we employed. Despite some limitations, the result is of sufficient significance that we have chosen to present this version of our analysis, the overriding conclusions of which we believe will not be significantly modified by the more complete, ongoing analysis. We emphasize that our spectral transformation approach is a crucial improvement over simply analyzing the data in the spacecraft frame without attempting to account for the large Compton-Getting anisotropy at these energies just above the solar wind speed.

OBSERVATIONS OF SUPRATHERMAL ION SPECTRA

The Cassini/MIMI/CHEMS instrument [3] is a time of flight mass spectrometer that measures the intensity of 3- to 220-keV/e ions, their elementary composition, and their charge state. Its field of view is 159° x 4° with the wide angle divided into three internal 53° "telescopes". The stepping electrostatic analyzer has a 3% energy per charge passband, which, along with the TOF measurement, determines mass per charge. An energy measurement by a solid state detector allows the mass and charge to be separately determined. Launched 15 October 1997, Cassini flew by Earth on 18 August 1999, bound for Saturn. On 30 December 2000, it flew within 135 Jovian radii (1 RJ = 71,400 km) of Jupiter, while 5.01 AU from the Sun and reached Saturn on 1 July 2004 at a 9.04 AU. The changing distance from the sun from the closest to farthest of the 18 events fully analyzed herein ranges from 4.88 to 9.01 AU.

In an earlier work the focus was on quiet times but here we examine active periods [4]. There are dozens of short-lived flux enhancements, which we have independently identified here. We require that 4.4, 13.6, and 41.6 keV protons all have hourly intensities above 501, 18.1, and 1.81 $cm^{-2}sr^{-1}s^{-1}keV^{-1}$, respectively. This selection was informed by study of many occurrence frequency vs. daily averaged counting rate distributions and counting rate time profiles but there was no clear rate threshold at which to set the limits, so we made reasonable choices to select moderate-to-high rate days. We also made a separate, more subjective, but careful, selection based of hourly counting rate vs. energy vs. time spectrograms and found no significant difference in the results. We thus identified 45 active periods of varying duration. At this point we are treating these events as equivalent in statistical wieght and are not accounting for the large variation in the duration, from 13 hours to 7.2 days for the 18 event subset discussed here. We have looked for relevant correlations between the duration of each event and the spectral index derived from the associated spectra and see no evidence that a different statistical weighting scheme will significantly change the results.

For the energy range considered herein, so near the solar wind speed, it is necessary to take into consideration the frame of reference of the measurements as compared to the theory. Even independent of a particular theory it is useful to analyze the data in a frame that is more fundamental to the physical processes involved. The spacecraft frame (SCF) is an arbitrary frame with respect to the physics of suprathermal tail development, so we desire to transform the observations into the the solar wind frame (SWF). The full

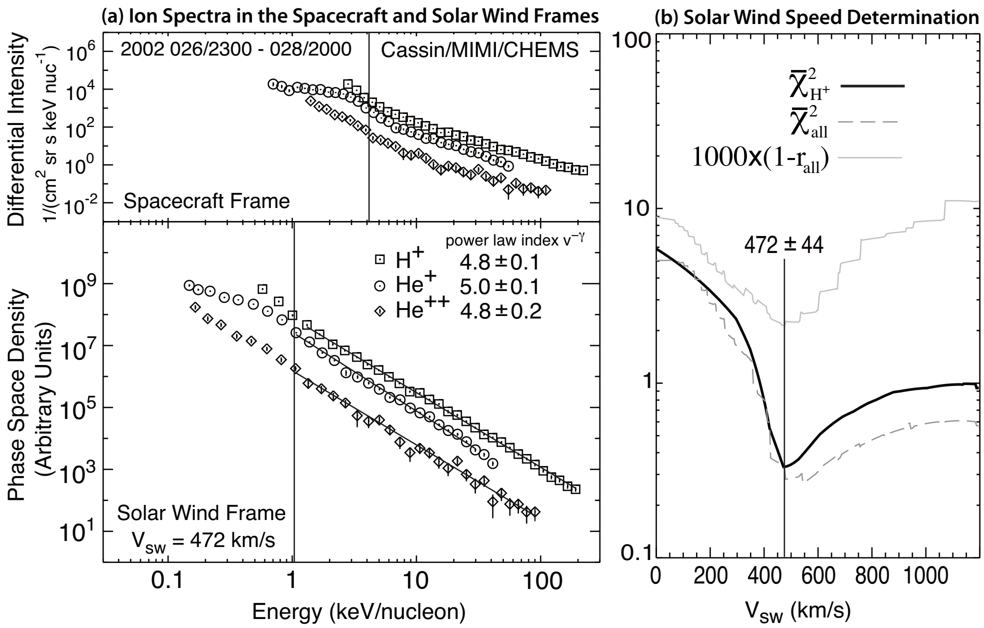

FIGURE 1. An illustrative example of the spectral and solar wind fitting procedures for a 2002 event lasting from day-of-year (DOY) 26, 2300 UTC to DOY 28, 2000 UTC. **(a)** H^+, He^+, and He^{++} differential intensity vs. energy/nucleon spectrum shown in the spacecraft frame (top) and phase space density vs. energy/nucleon spectrum in the solar wind frame (bottom) using the techniques described in the text. A least squares power law fit results in the displayed indices in velocity v. The pickup ion cutoff can be seen in He^+ at about 4 keV/nucleon in the spacecraft frame; i.e., at twice the solar wind speed, that speed being indicated in each of the frames of reference by a vertical line. Here the solar wind speed of 472 km/s was selected based on the analysis associated with panel (b). **(b)** The solar wind speed was determined by identifying the solar wind frame transformation that best resulted in a power law spectrum (of arbitrary slope) in the protons. The dark solid line is the reduced χ^2 for power law fits to the proton spectra; the dashed line is the same but for a combination of all three species; and the thin grey solid line is a modification of the linear correlation coefficient for the combined fits to the three species. The best fit speed and uncertainty, based on a 20% increase over the minimum $\overline{\chi}^2_{H^+}$ value is shown.

transformation was written down for the non-relativistic case by Ipavich [5] and involves a transformation of the energy and direction of incoming particles between reference frames. He implicitly starts with the Galilean transformation $\mathbf{v} = \mathbf{u} - \mathbf{V_{sw}}$, where we use $\mathbf{u}$ and $\mathbf{v}$ for the particle velocity in the SCF and SWF, respectively, and $\mathbf{V_{sw}}$ for the solar wind (frame translation) velocity.

The direction and energy (in a given measured energy and angular bin) are "mixed" through the transformation. For instance a given spectrum of particles all measured to have a single direction of motion in the SCF will correspond to particles of many velocities moving in a range of directions in the SWF. Likewise a collection of particles of the same speed, but with a distribution of directions in the SCF will correspond to a collection of particles of multiple energies traveling at a range of directions in the SWF.

This can be simplified because most of the particles we measure are observed to arrive at CHEMS in the telescope (usually telescope 3) most closely directed towards the Sun. So we can just assume a small angular offset $\vartheta = 20^\circ$ between the look direction and the sun-spacecraft line (in the SCF), but assume isotropy in the SWF to obtain a relationship for particle speed $v = \sqrt{u^2 - 2uV_{sw}\cos\vartheta + V_{sw}^2}$ (where u, v, and V_{sw} are the magnitudes of $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{V_{sw}}$, respectively), which we rewrite in terms of particle energy/nucleon, as follows:

$$E = \varepsilon + E_{sw} - 2\sqrt{\varepsilon E_{sw}}\cos\vartheta,$$

where $E_{sw} = \frac{1}{2}mV_{sw}^2$ is the kinetic energy/nucleon of a solar wind particle, with m the mass of a nucleon, 1 u, and likewise $\varepsilon = \frac{1}{2}mu^2$ and $E = \frac{1}{2}mv^2$ are the particle energies/nucleon in the SCF and SWF, respectively, again, all treated non-relativistically. This relation allows us to make a one-to-one relationship between the phase space density measured at a give energy in the SCF with the energy in the SWF, allowing us to now represent the spectrum not in the arbitrary spacecraft frame, but in the more fundamental solar wind frame.

The limitation of the method we employ here is that we are ignoring the anisotropy information that CHEMS offers with its three telescopes by using only Telescope 3. A problem that cannot be avoided is that the instrument capable of measuring the solar wind speed on Cassini has not been able to do so except in very limited time intervals (totaling in the 10's of days) because the spacecraft was rarely oriented such that any solar wind enters the Cassini Plasma Spectrometer (CAPS)[7]. Fortunately CHEMS can make a determination of the solar wind speed using a method we have used before and a method that arose in the context of the present study. The first method involves identifying the cutoff in the pickup ion spectra at approximately twice the solar wind speed [6]. Results from this method have been compared to the solar wind speed measurements from CAPS where the data are available, in particular during one month of data at the beginning of 2004, and has shown reasonable agreement.

The second method relies on the assumption that the spectral form of the suprathermal spectra will be a power law of arbitrary slope in the SWF. To determine solar wind speeds, we have used the latter method and tested for consistency with the pickup ion cutoff, and usually found approximate agreement. Although it is unfortunate that we do not have an independent solar wind speed to use, we do not believe that this limitation introduces excessive uncertainty into the calculations. We point out that at energies above the Compston-Getting-induced turn up in the spectra in the SCF (from about 3- to 5-times the solar wind speed to the top of the energy range), the power law index is often already close to -5. Although not yet definitive, the methods we use here are a significant improvement on the practice of simply analyzing the data and fitting spectra in the SCF (a practice which is however justified at sufficiently high particle energies).

We proceed by first converting our SCF differential intensities to phase space densities. Then we do a two-stage parameter search in which we set a solar wind speed, transfer to the solar wind frame, and then do a linear least squares fit to the log of phase space density versus the log of energy (equivalent to a power law). We tabulate the fit parameters and run through a range of solar wind speeds, performing the same analysis at each speed. The best solar wind speed is selected by choosing the speed that mini-

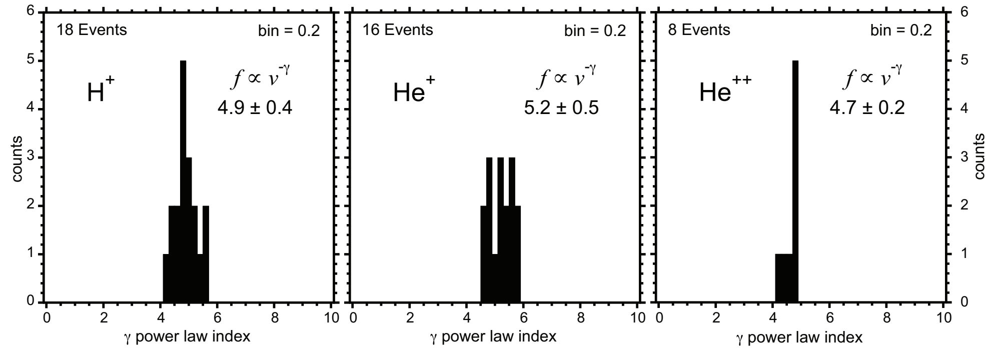

FIGURE 2. Histograms of power law indices from fits to proton, He^+, and alpha particle spectra from 18, 16, and 8 active periods, respectively. The mean and standard deviation of these sets of indices are given by 4.9±0.4, 5.2±0.5, and 4.7±0.2 for H^+, He^+, and He^{++}, respectively.

mizes the reduced chi squared $\overline{\chi}^2_{H^+}$ of the proton fits (Figure 1). We then use the spectra and spectral indices for all three ion species using the optimum solar wind speed for the frame transformation. We determine the fitting uncertainties, which are shown in Figure 1a, and the systematic uncertainties for each fit (discussed below).

STATISTICAL ANALYSIS OF SPECTRAL INDICIES

Once we determined the SWF-tranformed spectra and fit parameters for the three species, H^+, He^+, and He^{++}, for each of the 45 events we selected a sub-sample of the events. The criterion we used was simply that our automated fitting procedure resulted in a $\overline{\chi}^2_{H^+}$ vs. V_{sw} curve for which a usable minimum obtained. For this interim analysis we did not perform additional analysis on the more difficult cases, although many of them should be quite amenable to analysis; e.g., in some cases the current averaging periods are too long, such that the solar wind speed varies significantly, therefore we will break up the longer periods into a number of shorter intervals with more nearly constant SW speeds. For the 18 events of our sub-set, protons were always fit well, but the fit procedure for the other two species sometime failed, where the automated fitting was attempted for He^+, and He^{++} at whatever the solar wind speed was determined to be by the proton analysis. (There are 16 events for He^+ and 8 for He^{++}.) We collected histograms of the three sets of indices and show them in Figure 2. The systematic uncertainties that we calculated for each individual fit (not shown) are based on the uncertainty in the best fit solar wind speed and we found them to be consistent with the standard deviation of the set of indices for each species. The values are 4.9±0.4 for H^+, 5.2±0.5 for He^+ and 4.7±0.2 for He^{++}. Clearly the spectra from these events adopt the $v^{-\gamma}$ form with γ close to -5. (The very presence of a power law at all is also a new result.) While perhaps not of direct statistical significance, to provide a single parameter representative of the spectral slope of suprathermal ions in this study we mention that average slope for the three species results in

$$f(v) \propto v^{-4.9\pm0.2}.$$

In terms of differential intensity vs. energy the average power law spectral index is 1.46±0.11, the individual indices being 1.4±0.2, 1.6±0.3, and 1.3±0.1 for H^+, He^+, and He^{++}, respectively. We make no claims here about the theoretic debate that is associated with the suprathermal tail observations, but we do believe that this study begins to put to rest the question as to whether or not the $f(v) \propto v^{-5}$ spectra are common in the heliosphere, thus requiring any complete theory of particle acceleration to show why the spectral slopes tend to be very close to -5.

SUMMARY

Compared to analysis in the spacecraft frame, we have made a significant improvement on the study of Cassini/MIMI/CHEMS H^+, He^+, and He^{++} during active periods in the heliosphere from 5 to 9 AU from the Sun by transforming the measuments from the spacecraft to the solar wind frame. We have a more complete analysis ongoing, but at this time we are able to show that above the pickup ion spectral cutoff the spectra are well fit by power laws with a phase space density vs. velocity index very close to -5 (i.e., 4.9±0.4 for H^+, 5.2±0.5 for He^+, and 4.7±0.2 for He^{++}). This study of the interplanetary suprathermal spectra in the low energy portion of the spectrum is the first one that is independent of the Fisk-Gloeckler collaboration, and thus the observational question of the dominance of the -5 spectral slope has received a notable confirmation and an extension to greater distances from the sun and new ion species. This represents a tightening of the constraints on theories that seek to predict the prevalent $\sim v^{-5}$ spectra, although we do not weigh in on the merits or deficiencies of various models.

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