Suprathermal ions in the solar wind from the
Voyager spacecraft: Instrument modeling and background analysis

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Abstract. Using publicly available data from the Voyager Low Energy Charged Particle (LECP) instruments, we investigate the form of the solar wind ion suprathermal tail in the outer heliosphere inside the termination shock. This tail has a commonly observed form in the inner heliosphere, that is, a power law with a particular spectral index. The Voyager spacecraft have taken data beyond 100 AU, farther than any other spacecraft. However, during extended periods of time, the data appears to be mostly background. We have developed a technique to self-consistently estimate the background seen by LECP due to cosmic rays using data from the Voyager cosmic ray instruments and a simple, semi-analytical model of the LECP instruments.

1. Introduction
The solar wind is a plasma consisting of electrons, protons, and other ions that flows out from the Sun at all times. During nominal conditions, or “quiet times,” the core of the velocity distribution of solar wind protons is roughly Maxwellian, with thermal temperatures on the order of 10 eV. Outside this Maxwellian core, the velocity distribution exhibits power law behavior beginning at around several keV in the solar wind frame [1].

The spectral index of this power law, $\gamma$, is observed to have a common value of 1.5 when expressed as $j \propto E^{-\gamma}$, where $j$ is the differential number flux and $E$ is the kinetic energy [2, 3, 4]. Other analyses show different values [5], with an apparent dependence on solar cycle [6].

Many theories exist for the formation of power laws, typically falling into the two categories of generalized shock acceleration [7, 8, 9] and stochastic acceleration [10, 11, 12, 13, 14, 15], though magnetic reconnection can also produce power laws [16, 17]. These mechanisms can of course operate in concert, and there is some evidence of this for stochastic and shock acceleration [18]. Many theories try to specifically address the formation of the common spectral index [19, 20, 21, 22, 23, 17]. More data is needed to help determine which of these theories best predicts the real world.

2. Data
The Voyager spacecraft were launched in 1977 and have been traveling outward through the heliosphere ever since, collecting useful solar wind data. In this study of suprathermal ions, we analyze data recorded by the Low Energy Charged Particle (LECP) experiment [24]. LECP consists of two subsystems, the Low Energy Particle Telescope (LEPT) and the Low Energy...
Figure 1. Measured 27-day, direction-averaged differential particle fluxes from the eight PL channels from the \textit{Voyager 1} (left) and \textit{Voyager 2} (right) LECP/LEMPA/α detector (denoted by different colored lines) and 27-day \textasciitilde 2.2 MeV differential fluxes from CRS (black lines).

Magnetospheric Particle Analyzer (LEMPA), each of which has several detectors. Here we focus on the LEMPA/α detector because of its lower low-energy threshold and less complicated priority scheme as compared to LEPT.

However, analyzing LECP/LEMPA/α data is challenging because it is sensitive to high-energy particles. Figure 1 shows the \textit{Voyager} LECP/LEMPA/α measured differential fluxes in eight energy channels averaged over look-angle (referred to as PL01, PL02, etc.) and averaged over 27-day time intervals, along with differential fluxes measured by the \textit{Voyager} Cosmic Ray System (CRS) [25]. The mean energy of the CRS energy channel (2.2 MeV) falls between the mean energies of the PL07 and PL08 channels (1.5 and 2.7 MeV, respectively). Hence the fluxes of the three channels should mostly track each other, and indeed they do during times of high fluxes. However, at other times, most noticeably in the late 1980s and mid-to-late 1990s, they differ by many orders of magnitude. In fact, during these times, the last channel of LECP is correlated strongly with the last CRS channel, which has a mean energy higher by nearly two orders of magnitude (170 MeV).

A strong correlation also exists between the LECP/LEMPA/α data and data from a channel of the LECP/LEMPA/β detector, referred to as EB05 [24]. Because the β detector faces the walls of the instrument, it is not sensitive to low-energy ions. However, both the α and β detectors are sensitive to high-energy particles that penetrate the walls of the instrument. Figure 2 shows the 27-day and look-angle averaged EB05 count rate vs. the 27-day PL01-PL08 differential fluxes. Notice that the correlation between the two data sets is nearly perfect when the differential flux in each channel is at its lowest, which agrees well with our comparison of the CRS and LECP/LEMPA/α data. This correlation has been noted before, and the background due to penetrating particles was estimated for a few specific time periods through an analysis of the LECP/LEMPA/α anisotropy data [26].

Here, we take a different approach: construct a mathematical model of the instrument’s response to high-energy particles, fit semi-empirical functions to measured cosmic ray fluxes, and convolve the two to determine the contribution of cosmic rays to the measured flux of LECP.
3. Analysis

To compare with data, we must compute $j_i$, the differential number flux at each energy channel, $i$. $j_i$ is defined through the relation $j_i = C_i / G_i$, where $G_i$ is further defined by the relation $G_i = G'(b'_i - a'_i)$. $G'$ is the calibrated geometric factor of each detector, and $a'_i$ and $b'_i$ are the calibrated lower and upper limits of each energy channel, respectively. We take the values of $G'$, $a'_i$, and $b'_i$ from [27]. $C_i$, the count rate, is found generally through the following equation

$$C_i = \sum_s \int \epsilon_i(E, \Omega, x) j_s(E, \Omega) dx d\Omega dE,$$

where $\epsilon_i(E, \Omega, x)$ is the detector efficiency for a given energy channel $i$, as a function of incoming particle energy $E$, species $s$, incoming particle direction $\Omega$, and incident particle position $x$.

We use spherical coordinates ($d\Omega = d\phi \sin \theta d\theta$) and make several assumptions to this very general equation for mathematical and conceptual simplicity:

(i) Axisymmetry, so as to make the $\phi$ integral trivial
(ii) Incoming flux is isotropic in the instrument frame of reference, such that $j(E, \Omega) = j(E)$
(iii) Incoming flux is from protons.

Axisymmetry is needed for mathematical tractability in the current analysis but could potentially be relaxed in a future study. For the second assumption, the largest source of anisotropy is the shifting of particle distributions from the solar wind frame to the measured frame, an effect that decreases with increasing energy. For typical solar wind bulk energies (of order 1 keV), the effect on a power law spectrum with the common spectral index in the solar wind frame is completely negligible by 1 MeV. Also, the CRS instrument has multiple apertures that measure different look directions at the same energy. The similarities in differential flux for the different apertures demonstrate that isotropy is a good assumption at these energies ($\sim 2$ and $\sim 5$ MeV) for most time periods. Since we are focusing in this analysis on the effects of high-energy penetrating particles, we can safely assume isotropy. The last assumption of just protons has been investigated, and is a very good approximation for the times considered. We will re-examine the assumptions of isotropy and just protons in a future study.

Figure 2. Measured 27-day differential particle fluxes from the eight PL channels (from the LECP/LEMPA/$\alpha$ detector), averaged over look-angle vs. EB05 count rate (from the LECP/LEMPA/$\beta$ detector). The colors represent the different channels.
With the above simplifications, $C_i$ becomes

$$C_i = \int R_i(E)j(E)dE,$$

where $R_i(E)$ is the energy response function, which we define as an integral of the efficiency over position and look-direction. We also assume that the size of the detector is small relative to the entire instrument, such that we can perform the position integral separately, obtaining a separable active area, $A(\theta)$. For our simple calculation, we assume $A(\theta) = A_f |\cos \theta| + A_s |\sin \theta|$, where $A_f$ is the surface area of the face of the detector, and $A_s = 2\piwl_0$, where $l_0$ is the thickness of the detector at normal incidence and $w = \sqrt{A_f/\pi}$ is the radius of the detector (assuming the shape of the detector is a circular cylinder). $l_0$ was determined to be 89.1 $\mu$m for Voyager 2 and 96.5 $\mu$m for Voyager 1 [27]. The entire active area, $A(\theta)$, is shown in Figure 3a (solid line), along with the contribution from just the side of the detector, $A_s |\sin \theta|$ (dotted line). Also shown is the active area, $A(\theta)$, multiplied by the angular weighting factor, $\sin \theta$ (dashed line).

An expression for the energy response function is then

$$R_i(E) = 2\pi \int_{\theta_i^b(E)}^{\theta_i^a(E)} \sin \theta A(\theta)d\theta,$$

where $\theta_i^a(E)$ and $\theta_i^b(E)$ are found through $\Delta^{SI}(E, \theta_i^{a,b}) = \{a_i, b_i\}$. $\Delta^{SI}(E, \theta)$ is the energy deposited in the detector, and $a_i$ and $b_i$ are the electronic thresholds, which differ from $a'_l$ and $b'_l$ at low energies due to the combined pulse-height defect. The electronic trigger thresholds for the first few channels are given in [27]. The rest we assume to be the same as the calibrated limits.

Particles lose energy as they pass through material, and there are several ways to estimate this process. One way is by taking the average energy lost, $\bar{\Delta}$, divided by the material’s thickness, $l$, a ratio usually referred to as the stopping power. Theoretically, this mean value is derived from a probability distribution of energy loss, $P(\Delta)$, where $\Delta$ is an arbitrary value of energy loss. However, this energy loss distribution is in general not symmetric about its most probable value, $\Delta'$, with a tail extending to high $\Delta$. For a given $l$, $P(\Delta)$ is more asymmetric at higher energies than at lower energies; for large thicknesses and/or lower energies, $P(\Delta)$ approaches a Gaussian [28]. Here, we use the most probable value as given by the Landau-Vavilov-Bichsel (LVB) equation, Equation (30.11) in [29], altering it slightly by limiting the total energy loss to $E$, the initial energy of the particle. With this modification $\Delta'$ behaves thusly (neglecting shielding for the moment): it equals $E$ until reaching the energy at which particles begin to pass through the detector, decreases with $E$ to its “minimum ionizing energy,” and then increases more slowly to a constant level (see [29] and references therein). The LVB equation does not compare well with experiments at low energies due to its simplified stopping cross-section. However, we chose to use it for this analysis due to its simple analytical form. Other estimates of the differential energy loss that are more accurate at low energies are not analytical, such as GEANT4 [30], which we will consider using to find the instrument response in a future study.

The instrument consists of both the detector itself and all the shielding and structural material surrounding it. Figure 3b shows the thickness of each material used in our model as a function of polar angle, $\theta$, measured relative to the boresight of the detector. For simplicity, we estimate the complex shielding and structure by a single 3 mm thick layer of W for $\theta > \theta'$, where $\theta' = 22.5^\circ$ is the half-angle of the aperture of the instrument. This approximation is reasonable since W has a much larger stopping power than any other component. Thicknesses of the Si detector and the Al foil, which acts as a light barrier, are obtained from [27]. The thicknesses in Figure 3b depend on $\theta$ due to simple geometric effects: surfaces that face perpendicular to the boresight,
Figure 3. Active area (left) and thicknesses (right) of various materials of the Voyager 2 LEC/M/LMPA/α detector as a function of polar angle, $\theta$, measured from the boreisght of the instrument. Calculations of the same quantities but for Voyager 1 are very similar; see text for the differences.

like the face of the detector, vary as $| \cos \theta |^{-1}$, and parallel faces, in this case just the side of the detector, vary as $(\sin \theta)^{-1}$. Note that the detector is parallel-facing between the angles $\theta_p$ and $\pi - \theta_p$, where $\theta_p = \arctan(w/l_0)$. We neglect any thickness of the Al outside the aperture as well as any shielding by the body of the spacecraft itself and the other instruments, again for conceptual and mathematical simplicity (and because the model works well without this level of detail in the shielding).

Using our shielding and detector thickness estimates as a function of polar angle, $\theta$, we first calculate the energy lost in the shielding (either Al or W), then if the particle has enough energy to have made it through the shielding, we calculate the energy deposited in the Si detector using the particle’s remaining energy. Figure 4 shows $\Delta_{\text{Si}}(E, \theta)$ as a color map. The shape of the map can be understood through the variation of shielding and detector thickness with $\theta$. For $\theta < \theta'$, the only shielding is a thin layer of Al, so particles pass through it with almost no energy loss except at the very lowest energies. For $\theta > \theta'$, low-energy particles are slowed significantly by the shielding, causing a cut-off around 100 MeV, while at the same time depositing the most energy around $\theta = 90^\circ$ because that’s where the detector is thickest. At high energies (>1 GeV) particles at all angles are not slowed much by the shielding, so the variation is completely due to the detector thickness.

From our calculation of $\Delta_{\text{Si}}$, we find $\theta_{a,b}^o$ and numerically calculate the integral in Equation 3. The result is shown in Figure 5, normalized by $G$, the ideal geometric factor of the instrument calculated with the following

$$G = 2\pi \int_0^{\theta'} \sin \theta A(\theta)d\theta.$$  

For $A(\theta) \approx A_f \sin \theta \cos \theta$ and $\theta' = 22.5^\circ$, $G$ is approximately equal to 0.115 cm$^2$-sr. Note that the Voyager calibrated geometric factors, $G'$, are slightly lower, 0.04 and 0.113 cm$^2$-sr for Voyager 1 and Voyager 2, respectively (see [27] for more information). In Figure 5, different channels are represented by different colors as denoted in the figure (the color scheme is the same as in Figures 1 and 2). At low $E$, the normalized response functions are box-like, with lower and upper limits occurring roughly at $a_i'$ and $b_i'$, respectively, which are shown as dotted lines in the figure. At the lowest energies, the responses are reduced in width and shifted to higher $E$ as compared to the calibrated limits, $a_i'$ and $b_i'$ due to energy losses in the Al layer. The LVB
Figure 4. Energy deposited in the Voyager 2 LECP/LEMPA/α detector as a function of incoming energy and polar angle for protons. Also shown are the channel thresholds (solid lines represent $a_i$ and the dashed line represents $b_8$).

equation is not as accurate for very thin targets [29], and so energy loss in the Al is probably overestimated in this analysis. Beyond $E \approx b_8$, the response continues with channels in reversed order and with the same height. Then, depending on the channel, the response rises about a decade, goes through a local minimum, and finally levels off to a value inversely proportional to the channel number. The much larger response beyond $\sim$100 MeV is due to the larger angular acceptance of the instrument at these energies.

The next step of the analysis is to estimate a model differential flux, $j$. Our chosen model spectrum consists of three components: a power law with an exponential roll-over due to suprathermal solar wind ions, a modulated power law due to galactic cosmic rays (GCRs), and another modulated power law due to anomalous cosmic rays (ACRs). For the suprathermal power law, we adopt a form equivalent to that given in [3], $j = c_0(E\ [\text{MeV}])^{-\gamma_0} \exp\left(-\left(E/E_0\right)^{\alpha_0}\right)$, where $E$ is particle kinetic energy, $\gamma_0$ is the spectral index at low energies, $c_0$ is the normalization constant, $E_0$ is the rollover energy, and $\alpha_0$ is the rollover sharpness index. For the GCR component, we use the “force-field” approximation [31] to modulate the spectrum: $j(E) = \left(\left(E + M\right)^2 - M^2\right)\left(\left(E + M + |z|\Phi\right)^2 - M^2\right)^{-1} j_\infty(E + |z|\Phi)$, where $|z|$ is the absolute value of the particle’s electric charge relative to the proton charge, $\Phi$ is the effective potential of modulation, and $M$ is the particle’s rest energy. Since we are just considering protons, $z$ and $M$ are 1 and 938 MeV, respectively. $j_\infty(E)$ is the spectrum at the boundary,
the form of which for this analysis we assume to be a triple power law [31]:

$$j_{\infty}(E) = c_1(E \text{ MeV})^{-\gamma_1}(1 + c_2(E \text{ MeV})^{-\gamma_2} + c_3(E \text{ MeV})^{-\gamma_3})^{-1}.$$  

For the ACR component, we use the diffusion-convection approximation to modulate the spectrum inside the termination shock [31],

$$j(E) = j_{TS}(E) \exp(-c_6((E + M)((E/M + 1)^{2/3} - 1)^{1/2}))^{-1},$$  

and a power law with an exponential-type rollover at high energies for the spectrum at the termination shock [31],

$$j_{TS}(E) = c_5(E \text{ MeV})^{-1} \exp(-c_4(E/62 \text{ MeV})^{\gamma_4}).$$

### 4. Results and discussion

Figure 6 shows as “x” symbols differential fluxes from Voyager 1 LECP/LEMPA/α in viewing sector 2 (see e.g. [32] for viewing direction definitions) averaged over the entire year of 1999, plotted vs. logarithmic mean channel energy, $E_i = \sqrt{a_i'b_i'}. The horizontal error bars show $a_i'$ and $b_i'$. The open circles represent data from Voyager 1 CRS averaged over the year 1999 [33]. Filled circles are year-averaged LEPT proton fluxes. Open diamonds represent CRS proton data as available on CDAWeb. The open squares represent data from instruments at 1 AU, as summarized in [34]. Although this data is taken at 1 AU and not during the same period, solar modulation has little effect at these energies. The dashed lines represent a fit of our model to the data, found with the parameters given in Table 1. The solid line represents $j_i$, our calculation of the spectra measured by LECP, given $j$, the model functions. Finally, the dotted line represents
Table 1. Parameters for the model fluxes. \( c_0, c_1, \) and \( c_5 \) have units of particles/(MeV·cm\(^2\)-sr-s), \( E_0 \) has units of MeV, and \( \Phi \) has units of MV. All other constants are unitless.

| \( j_0 \)        | \( 9.5 \times 10^{-4} \) | \( 9.5 \times 10^{-4} \) |
| \( \gamma_0 \)   | 1.5                        | 1.5                        |
| \( E_0 \)        | 2.6                        | 2.6                        |
| \( \Phi \)       | \( 2.0 \times 10^2 \)     | \( 2.0 \times 10^2 \)     |
| \( c_1 \)        | \( 5.3 \times 10^5 \)     | \( 5.3 \times 10^5 \)     |
| \( \gamma_1 \)   | 2.8                        | 2.8                        |
| \( c_2 \)        | \( 1.3 \times 10^4 \)     | \( 5.6 \times 10^4 \)     |
| \( \gamma_2 \)   | 1.0                        | 1.3                        |
| \( c_3 \)        | \( 2.8 \times 10^8 \)     | \( 2.8 \times 10^8 \)     |
| \( \gamma_3 \)   | 2.9                        | 2.9                        |
| \( c_4 \)        | 1.9                        | 1.9                        |
| \( \gamma_4 \)   | 2.5                        | 2.5                        |
| \( c_5 \)        | 1.0                        | 1.0                        |
| \( c_6 \)        | \( 8.0 \times 10^2 \)     | \( 8.0 \times 10^2 \)     |

the calculated flux of LECP for \( E > 4.0 \) MeV (not visible under solid line).

For illustrative purposes, we also show, as solid colored lines, the normalized response, \( R/G' \), multiplied by the input differential flux, \( j \), for each energy channel of the detector (PL01-08), with the same color scheme as in Figures 1, 2, and 5. These lines represent the integrand of equation 2, with the calibrated geometric factor, \( G' \), factored out in order to show that at the lower energies, \( R/G' \) times \( j \) equals the incident model flux. Naturally, these curves rise at a certain energy, just as the response does, but then quickly fall, following the trend of the input model flux. Note that, although the lowest energy portions of the integrand are comparable to or higher than the higher energy portions, they contribute very little to the total expected flux in each channel. This is because it is the area under each curve that matters, and the width of the lower energy portions is extremely small compared to the widths of the curves at higher energies (the horizontal axis is logarithmic).

Using a simple model for the instrument and a simplified formula for the energy deposition of protons in the shielding and detector, combined with a realistic model for the flux of cosmic rays, we have shown that the basic shape and overall level of flux from Voyager LECP/LEMPA/\( \alpha \) is reproduced. Thus, we have shown, through our physics-based approach, that cosmic rays do indeed cause the background in LECP. However, the detailed shape is not matched exactly. To match the shape exactly, a more accurate but complex description of the instrument and a more accurate but non-analytical method of determining the energy deposition in the shielding and detector may be needed. With these improvements to the model, we hope to remove the cosmic ray background to estimate the flux of suprathermal particles in the heliosphere and beyond. In a future study, we plan to compare our method with existing methods, most notably an empirical method that uses the LEMP/\( \beta \) detector data.

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Figure 6. Differential flux vs. kinetic energy. “x” symbols are Voyager 1 (left) and Voyager 2 (right) LECP/LEMPA/α data from viewing sector 2 averaged over the entire year of 1999. Open circles are proton fluxes from Voyager 1 CRS as presented in [33]. Open squares represent proton data taken at 1 AU, as presented in [34]. Filled circles are year-averaged LEPT proton fluxes. Open diamonds represent CRS proton data as available on CDAWeb. The dashed line is the model input flux. The solid black line is the model output flux. The solid colored lines represent the normalized response (\(R/G\)) multiplied by the incident flux for each channel, PL01-08. The dotted line (not visible under solid black line) is the model output flux corresponding to the input flux between 4 MeV and 1 TeV.

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