Recent Particle Measurements from Voyagers 1 and 2

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Abstract. We summarize recent measurements made by the LECP instrument on Voyager 1 near its crossing of the heliopause and entry into the interstellar medium on or about day 238 of 2012 at 121.6 AU, and on Voyager 2 mainly during the period 2012-2014.4 characterized by large variations in the intensities and angular distributions of low-energy heliosheath ions and the reappearance of low-energy heliosheath electrons. Results from Voyager 1 not previously published include the energy dependence of ion intensity decreases prior to the heliopause crossing and a quantitative measure of the evolution of low-energy heliosheath proton pitch angle distributions that extend across the heliopause. For Voyager 2 we describe the evolution in time and with ion energy of the tangential streaming of ions directed from the nose toward the tail of the heliosheath, summarize the recovery of low-energy heliosheath ion intensities since their decline to minimum levels during 2013.0-3013.3, and discuss the effects of this intensity minimum and subsequent recovery on the ion partial pressure in the heliosheath and on its magnitude relative to that of the thermal plasma and the magnetic field.

1. Introduction
Voyager 1 (V1) and 2 (V2) are receding from the Sun at 3.58 AU yr−1 (17.0 km s−1) and 3.24 AU yr−1 (15.4 km s−1) respectively, and are now at respective heliocentric radii 127.8 AU and 104.8 AU (23.0 AU separation), heliographic latitudes N34.6° and S30.7° (65.3° separation), heliographic inertial longitudes 174.4° and 217.6° (43.2° separation; the latitude and longitude of inflow from the local interstellar medium (LISM) are ≈0° and 175°, respectively; so V1 is near the heliospheric nose). Their rectilinear separation is 145.5 AU. V1 crossed the termination shock (TS) of the solar wind on 16 Dec. 2004 at 94.0 AU [1-4], and explored the shocked solar wind in the heliosheath (HS; ≈30 AU wide along the V1 path) for ≈8.2 years. On or about 25 Aug. 2012, V1 at 121.6 AU entered a new region characterized by an increase in the magnitude of the magnetic field and of the intensity of galactic cosmic rays (GCR), and by large reductions in the intensity of TS ions and electrons and of anomalous cosmic rays (ACR) [5-8]. It is believed that around that time V1 crossed the heliopause (HP), the boundary separating plasma of solar origin from that of the LISM, and is now in the LISM [5,9]. V2 crossed the TS several times on 29-31 Aug. 2007 at 83.65 AU [10-13] and is now in the HS, ≈21 AU beyond the TS, as it heads toward the HP. Each Voyager carries a nearly identical set of instruments that continue to monitor plasma, field, and energetic particle activity in the HS and LISM (the exception is that only V2 has a working plasma instrument). This paper is a survey of recent measurements made during ≈2012-2014.4 by the Low Energy Charged Particle (LECP) instruments [14] on V1 and V2.

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2. Voyager 1 near the heliopause crossing

Figure 1 shows particle intensities measured at V1 during 2012.5-2012.7 in seven low-energy ion (single-parameter: total energy) channels covering 0.05-4.0 MeV, two proton (two-parameter: total energy, species) channels covering 3-31 MeV, a galactic cosmic ray (GCR) proton channel >211 MeV, and a low-energy electron channel 0.04-0.07 MeV. All traces are daily averages and were corrected for background as necessary. The two grey-shaded intervals during days 210-215 and days 226-234 are periods when intensities of low-energy ions and protons 0.05-31 MeV and low-energy electrons decreased while those of GCR protons and electrons increased and the magnitude of magnetic field increased [5-8]. The grey-shaded period from day 238 onward denotes V1 beyond its HP crossing. In the LISM the intensities of the ion channels and the electron channel decrease to background levels, the 3-17 and 22-31 MeV proton intensities, which are mainly ACRs, extend into the LISM with decreasing intensities, and the GCR protons increase to their highest levels measured prior to day 238 [5-7]. Aside from the GCRs, all channels displayed in figure 1 are evidently of heliospheric origin.

2.1. Energy dependence of intensity decreases in the first depletion region

We refer to days 210-215 and 226-234 of 2012 as the first and second depletion regions respectively. In the first depletion region intensities decrease in all channels except that of >211 GCR protons, which increases, and all remain above background except the electron channel. In the second depletion region the ion and proton intensity decreases are larger, and the lower-energy ion channels and the

![Figure 1](https://example.com/figure1.png)

Figure 1. Daily averaged intensities of low-energy ions (0.05-4.0 MeV), protons (3-31 MeV), electrons (0.04-0.07 MeV), and >211 MeV GCR proton count rates measured at V1 during 2012.5-2012.7. Grey-shaded periods during day 210-215, 226-234, and after day 238 indicate periods when V1 was in the first and second depletions regions and then evidently in the LISM.
electrons drop to background levels. A noted in [6], the electron intensity begins a gradual exponential decrease starting \(\approx 2012.52\) that continues until the first depletion region, then recovers slightly for 3-4 days between the two depletion regions, and then drops to background levels. This trend is markedly different from those of the low-energy ions and protons, which decrease only gradually, if at all, before, between and after the depletion regions and up until the HP crossing into the LISM. The nature of the HS and the HS depletion regions and variations of the particle populations and magnetic field [7] have been interpreted differently by various authors [6,9,16-18].

We examine in figure 2 the energy dependence of the 0.05-30 ion and proton intensity decreases in the first depletion region. For each channel we calculated the average intensity during the three-day depletion period 211-213, which excludes intensities within one day of the “edges” on days 210 and 215, and during the three-day pre-depletion period 207-209 just ahead of the first depletion. The ratio of intensity before to that during the first depletion, denoted as \(R_D\) in figure 2, is plotted versus the particle’s geometric mean speed, \(v = \left[2(E_L E_H)^{1/2} / m_p\right]^{1/2}\), where \(E_L\) and \(E_H\) are the lower and upper energy passband of a channel, \(m_p\) is the proton mass, and we have assumed that protons dominate the intensities in the seven ion channels. The large error bars in the lowest three channels are due to reduced count rates when the large background contributions are removed from these channels. The nine error-weighted points are well fit by a power-law in \(v\) with exponent \(-0.44 \pm 0.03\) (-0.45 \(\pm\)0.03 if we neglect the lowest three channels), indicating a rather weak dependence, \(R_D \approx r_g^{-1/2}\), on the proton gyroradius \(r_g\). This relation may be useful in future modelling to determine the energy dependence of, e.g., the escape of ions from HS flux tubes reconnected to LISM fluxes tubes [15,17], or the filling of LISM flux tubes that intrude into the HS [6]. For example, in the interchange scenario advocated by Krimigis et al. [6], we would expect higher energy ions with larger gyroradii to fill empty LISM tubes more rapidly, as observed in the two depletion regions. However, details remain to be worked out.

2.2. Angular distributions of 3-31 MeV protons after the HP crossing

Krimigis et al. [6] discuss the evolution of the 3-17 MeV proton pitch-angle distributions (PADs) before and after the HP crossing (red trace in the right panel of figure 1). Florinski et al. [19] published model calculations that reproduce these data. For completeness, we show in figure 3 the PADs of higher-energy, 22-31 MeV ACR protons. The time evolution and interpretation of these PADs are

Figure 2. Ratio \(R_D\) of proton intensity on days 207-209 before first intensity depletion to that on days 211-213 during the depletion at V1 in 2012 (see figure 1) versus geometric mean speed \(v\) of the energy channel. Fit is an error-weighted power law \(R_D = A v^{-0.44 \pm 0.03}\).

Figure 3. Evolution of 22-31 MeV proton PADs before and after HP crossing. Pie plots are PADs in LECP scan plane (inset shows sector numbers). Light-shaded sector 4 is blocked. Red vector in pie plots is the direction of \(B\), measured by V1 MAG, that lies nearly in LECP scan plane.
very similar to those of the 3-17 MeV protons, and we refer to Krimigis et al. [6] for details. We simply note that the first three PADs in figure 3 indicate that before the HP crossing, magnetic conditions along field lines were producing asymmetric loss-cone distributions along the magnetic field $\mathbf{B}$, while after the HP crossing, the PADs developed pancake distributions, i.e., intensities are peaked transverse to $\mathbf{B}$, and in the LISM intensities in all sectors rapidly decrease.

In figure 4 we examine the evolution of the 3-17 MeV proton anisotropy after the HP crossing. The lower panel shows intensities in four of the seven active sectors, color-coded as indicated in the legend, with sector view direction in the LECP scan plane indicated in the inset pie plot. As a measure of the anisotropy, we plot in the upper panel the ratio ($R$) of the sum of sector 1 (S1) and S5, which measure protons spiralling nearly perpendicular to the $\mathbf{B}$, to the sum of S3 and S7, which measure protons moving nearly parallel and anti-parallel to the $\mathbf{B}$, respectively. The number of counts in S3 and S7 are sufficient to give a statistically significant ratio $R$ for $\approx 10$ days after the HP crossing (grey-shaded period). The red dashed line is an exponential fit to the points during this period. The anisotropy increases away from the HP with an e-folding time of 4.5 days, which translates to an e-folding distance of 0.045 AU or $\approx 7$ gyroradii of a 3-17 MeV proton in a 0.4 nT magnetic field [7] when we convert time to distance using the radial speed of the spacecraft ($\approx 0.01$ AU day$^{-1}$).

3. Voyager 2 observations in the heliosheath

3.1. Tangential anisotropy of 0.03-30 MeV protons in 2013

We turn now to measurements made by the V2 LECP in the HS. Figure 5(a) shows five-day running averages of daily intensities, from the TS crossing on 2007.65 to 2014.4, of 28-43 keV ions moving in

![Figure 4](image.png)

**Figure 4.** Bottom: Count rates in four of seven active sectors (S4 is blocked) of 3-17 MeV protons at V1. Top: Ratio of S1+S5 that detect protons gyrating nearly transverse to magnetic field vector $\mathbf{B}$, to sectors S3+S7 that detect protons moving along $\mathbf{B}$.

![Figure 5](image.png)

**Figure 5.** (a) Intensity of 28-43 keV ions moving in $+T$ (red) and $-T$ (black) direction. (b) 1st-order anisotropy vector, (c) associated relative amplitude $A_1/A_0$ and (c) azimuth angle $\phi_1$. (d) Relative 2nd-order anisotropy amplitude and (e) associated azimuth angle $\phi_2$. 


the $+T$ direction (red trace and shading) and the $-T$ direction (black trace) (the $\pm T$ direction conforms to the usual heliospheric $RTN$ coordinate system). This is the lowest-energy ion channel on either V1 or V2, with the mean speed of measured protons being $\approx 1.5$ AU day$^{-1}$. The larger intensity in the $+T$ direction is generally consistent with a convective anisotropy due to the HS plasma velocity having components in the $+R$ and $+T$ directions that are of comparable magnitudes at V2 [20]. However, as described below, there are periods of interest that indicate contributions to the low-energy ion channels from heavy ions and from $b\text{ona~fide}$ field-aligned anisotropies in the HS. Figures 5(b)-5(f) show the results of a least squares Fourier fit to the angular data taken in eight 45° sectors in the V2 LECP scan plane, which is nearly parallel to the $R$-$T$ plane [14,21]. These data are fit to the function

$$j(\phi) = a_0 + a_1 \cos(\phi) + b_1 \sin(\phi) + a_2 \cos(2\phi) + b_2 \sin(2\phi),$$  \hspace{1cm} (1)$$

where $j$ is intensity, the fit coefficients are $(a_0, a_1, b_1, a_2, b_2)$, and azimuth angle $\phi$ is measured in a right-handed sense from the $R$- to the $T$-axis. Equation (1) can be written in the more convenient form

$$j(\phi) = A_0 + A_1 \cos(\phi - \phi_1) + A_2 \cos(2(\phi - \phi_2)).$$  \hspace{1cm} (2)$$

Here, $A_0 = a_0$, $A_1 = (a_1^2 + b_1^2)^{1/2}$ and $\tan \phi_1 = b_1/a_1$ ($k = 1,2$) are calculable from $(a_0, a_1, b_1, a_2, b_2)$.

Figure 5(c) is the relative first-order anisotropy amplitude $A_1/A_0$, where $A_0$ is the sector-averaged intensity, and panel (d) the associated direction $\phi_1$. Figure 5(b), constructed from the best-fit coefficients in panels (c) and (d), is a vector pointed in the direction that particles are moving (see inset showing $R$, $T$, $R$ axes), with magnitude given in panel (c). Figure 5(e) is the relative second-order anisotropy amplitude $A_2/A_0$ and panel (f) the associated direction azimuth $\phi_2$ (see [21] for details).

We will focus on the period in 2012-13 leading up to the large increase of $A_1/A_0$. During this period, which corresponds roughly to the interval 2012.45-2013.30 between the vertical dashed lines labelled B and C in figure 5, the intensity drops while the angle $\phi_1$ rotates from $\approx 45^\circ$ to $\approx 80^\circ$ (not quite 90° because intensities in the spacecraft frame include radial convection). Around 2013.3 the intensity reaches its lowest value while $A_1/A_0$ reaches its highest value yet observed at V2 in the HS. This period is also marked by large and sporadic fluctuations in $A_1/A_0$ due to the sporadic increases in the anisotropy amplitude. We attribute the enhanced $A_1/A_0$ during 2009.3-2010.5 to suprathermal pickup He$^+$ or O$^+$ ions, or both, that were boosted in energy at the TS, convected to V2 by the $\approx 200$ km s$^{-1}$ HS flow, and measured by the LECP instrument, which responds to He and O ions with energies 9-40 keV nuc$^{-1}$ and 4-15 keV nuc$^{-1}$ respectively. Although it is unclear why these heavy ions are prevalent at V2 during 2009.3-2010.5 (solar minimum), we note that pick-up O$^+$ ions were measured by the V1 and V2 LECP instruments in high-speed solar wind flows during the 1995-1998 solar minimum [22].

Figure 6(a) shows daily intensities of $+T$-directed (blue) and $-T$-directed (black) 43-80 keV ions at V2 during 2010-2014.4. Also shown for reference is the sector-averaged intensity of a 43-80 keV ion channel from V1 (this channel is synthesized using two V1 energy channels 40-53 and 53-85 keV). Figure 6(b) shows the $T$-component of the relative first-order anisotropy vector $\xi_{it} = (A_i/A_0)\sin \phi_i$. Panel (b) illustrates the gradual increase in $\xi_{it}$ and then a spike-like jump as the 43-80 keV ion intensity approaches a minimum, followed by an abrupt drop of $\xi_{it}$, coincident with an increase in the intensity on 2013.30 (line C). The essential point is that although both $+T$- and $-T$-directed ions were decreasing in a quasi-exponential manner during $\approx 2012.5$-2013.30, the $-T$-directed intensity decreased more rapidly during $\approx 2013.0$-2013.3. It is this relative reduction in the ions reaching V2 from the tailward direction relative to those reaching V2 from the noseward direction of the HS that produced the bulk of the growing $+T$-directed anisotropy. In addition, close examination of the V2 traces in figure 6(a) just prior to the peak of $\xi_{it}$ shows that the $+T$-directed ions actually began
increasing at least ten days before the -T-directed ions, and it is this early rise in tailward-directed ions that gave rise to the spike.

In summary, the gradual increase in $\xi_{1T}$ during the intensity drop results from fewer ions coming from the HS tailward of V2 compared to those coming from the HS noseward of V2, and the large spike in $\xi_{1T}$ results from a +T-directed (or tailward-directed) increase in ion intensity from a probable "source" noseward of V2 arriving several days before the corresponding increase in the –T-directed (or noseward-directed) intensity increase. It is plausible that the ≈10-day delay in the rise time of these two oppositely directly populations represents the scale time required for the tailward moving ion population to scatter or mirror and return to V2 as part of the noseward moving component (e.g., the average proton speed ≈1.9 AU/day at a 30° pitch angle implies a transit distance ≈ 16 AU).

There was a similar, but smaller, increase in $\xi_{1T}$ as the 43-80 ion intensity decreased during 2010.7-2011.2, followed by an abrupt decrease in $\xi_{1T}$, again coincident with an intensity increase on 2011.2 (line A in figure 6(b)). The anisotropy evolution during these two intensity decreases shows that as the ion intensity drops, there is a net streaming of ions measured at V2 that is toward the flanks of the HS, i.e., again away from the nose (from the direction of the V1 azimuth) and toward the tail. Figure 7 shows that this net streaming is present in ion and proton channels that extend from ~0.03 to 20 MeV (the same streaming is seen in the 22-30 MeV proton channel, not shown here, extending this range to 30 MeV). Periods with large +T-directed streaming are the only periods when the T-component of plasma flow measured by the V2 plasma instrument and also estimated from Compton-Getting analysis of the LECP low-energy ion angular distributions show significant differences [20].

Figure 6. (a) Intensity of ions 43-80 keV moving in the +T (blue) and –T direction (black) at V2, and sector-averaged ions 43-80 keV at V1 (green). (b) T-component of 1st-order anisotropy vector $\xi_{1T} = (A_t / A_n) \sin \phi_1$ (in RTN system).

Figure 7. (a) Sector-averaged intensity of ions 28-43 keV at V2. (b) 1st order anisotropy of ions 28-43 keV, (c) ions 80-137 keV, (d) ions 220-550 keV, and (d) protons 3-17 MeV. Vertical dashed lines labelled A-C are defined in the text.
3.2. Partial recovery heliosheath particle intensities at V2

Figure 8 is an overview of energetic particle activity at V2 during the 1.8-year period 2012.5-2014.3. Plotted are daily intensities in eight ion channels covering 0.03-3.5 MeV, 2 proton channels covering 3-30 MeV, and an electron channel 0.04-0.06 MeV. There is a decline of all ion intensities to minima at slightly different times that depend on energy. Ions with energies >0.5 MeV reach sharp minima around 2013/008 (year/doy; first vertical dashed line), while ions 0.03-0.5 MeV reach broad minima in the ≈100 day period between the first dashed vertical line at 2013/008 and line C at 2013/110, where the lower energy ion channels increase abruptly, while higher energy ions show local peaks. Line C also marks the return at V2 of low-energy heliospheric electrons with energies from a few tens of keV to one MeV (only the 0.04-0.06 MeV electrons are shown here). Note that the abrupt increase of the intensities of lower-energy ions, generally consistent with being the suprathermal tail created when pickup protons are heated and mildly accelerated at the TS [23], and the electrons and the abrupt cessation of the +T-directed ion streaming anisotropies coincide. At 2013/273 (line D) there are increases in all the ion channels that are qualitatively similar to those that occurred on 2013/110. Although another decrease in ion intensities occurred late ≈2013.9, the intensities of the lower energy ions and the electrons have continued to increase in the most recent data examined.

3.3. Variations of suprathermal ion partial pressures

Figure 9(a) shows intensities of ≈80-140 keV ions at V1 and V2 during 2007.5-2014.4, the roughly 7-year period V2 has been in the HS. Figure 9(b) compares the partial pressures of suprathermal ions

![Figure 8](image-url)  
**Figure 8.** Stack plot of daily-averaged intensities in 8 ion and 2 proton channels covering 0.03-30 MeV and one electron channel 35-61 keV from the V2 LECP in 2012.5-2014.4. Traces have been offset vertically for clarity. Plotted for reference is the V1 LECP 3.4-17.6 MeV proton channel showing the abrupt drop on ≈2012/238 when V1 crossed the HP.

![Figure 9](image-url)  
**Figure 9.** (a) Daily intensities of ions ≈80-140 keV at V1 and V2, 2007.5-2014.4. (b) Partial pressure of protons at V1 (0.04-4.0 MeV) and V2 (0.03-3.5 MeV). (c) V2 ion pressure from panel (b) compared to plasma and magnetic pressures. (d) Plasma beta with (β+) and without (β) low-energy ion pressure included.
(assumed to be protons) at V1 and V2. Line C indicates where +T-directed ion streaming at V2 abruptly stopped and ion intensities increased. Figure 9(c) compares the partial ion pressure at V2, reproduced from panel (b), with the magnetic field pressure $P_{\text{MAG}} = B^2 / 8\pi$, where $B$ is the field magnitude measured by the V2 Magnetometer (MAG), and plasma pressure $P_{\text{PLS}} = (1+0.35)Nk_B T_p$, where $N$ is the plasma density and $T_p$ the proton temperature measured by the V2 Plasma Science (PLS) instrument [10], and $k_B$ is the Boltzmann constant (corrected data from the V2 MAG beyond 2010 were unavailable at this writing). We have set the electron temperature to 0.35 $T_p$, consistent with measured post-TS temperatures $T_p \approx 10^5$K and $T_e \approx 3-4 \times 10^4$K [10]. Figure 9(d) shows the plasma beta (ratio of particle pressure to magnetic pressure), with $\beta = P_{\text{PLS}} / P_{\text{MAG}}$ calculated using the plasma pressure only, and $\beta' = P_{\text{PLS-LECP}} / P_{\text{MAG}}$ calculated using the combined plasma and low-energy ion pressures. Quantity $\beta$ varied about unity from the TS crossing until mid-2008 and then decreased by a factor $\approx 2-3$ through 2010. Quantity $\beta'$ remained well above unity and showed large fluctuations about an average $\approx 5$ that are due mainly to variations in $B$ from the TS crossing through 2010. The large value of $\beta'$ reflects the dominant role played by pickup protons in maintaining pressure balance in the HS [10,11,24]. However, since the bulk of the HS pickup proton population with energies above a few hundred eV are not measured by either the V2 PLS or LECP instruments, $\beta'$ greatly underestimates the actual HS beta that includes the full energy spectrum of pickup protons heated and accelerated at the TS and possibly in the HS [10,11,16,24].

The evolution of the low-energy ion intensities in the 80-140 keV and other channels from the V1 and V2 LECP were remarkably similar, on average, until the V1 HP crossing. The partial pressures in panel (b) also evolved similarly, showing about the same magnitude and decay rate in $\approx 2012.0-2013.0$. The lowest pressure at V2 of $\approx 5.5 \times 10^{-14}$ dyne cm$^{-2}$ occurred in $\approx 2013.0-2013.15$, representing a 7-fold drop from the post-TS peak of $3.5 \times 10^{-13}$ dyne cm$^{-2}$ in 2007.8, and a 3-fold drop from the peak pressure in 2011. Since the suprathermal ion partial pressure is only $\approx 15\%$ of the total pressure in the heated pickup proton population in the HS [24], it is clear from figure 9(c) that the HS remains a high beta plasma, unless of course there are large increases in the magnetic field amplitude that have not yet been reported.

4. Summary
We have briefly summarized measurements made by the LECP instrument on V1 near its crossing the HP and entering the LISM on or about day 238 of 2012 at 121.6 AU, and on Voyager 2 mainly during the period 2012-2014.4 characterized by large variations in the intensities and angular distributions of low-energy HS ions and the reappearance of low-energy HS electrons. Results from V1 not previously published included the energy dependence of ion intensity decreases prior to the HP crossing and a quantitative measure of low-energy HS proton pitch angle distributions extending across the HP into the LISM. For V2 we described the evolution in time and with ion energy of the tangential streaming of ions that is directed from the nose toward the tail of the HS, summarized the recovery of low-energy HS ion intensities since their decline to minimum levels during 2013.0-3013.3, and discussed the implications of this intensity minimum and its subsequent increase on the ion partial pressure in the HS and its magnitude compared to those of the thermal protons and the magnetic field.

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