On the Energy Dependence of Galactic Cosmic Ray Anisotropies in the Very Local Interstellar Medium

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Abstract

We report on the energy dependence of Galactic cosmic rays (GCRs) in the very local interstellar medium (VLISM) as measured by the Low Energy Charged Particle (LECP) instrument on the Voyager 1 spacecraft. The LECP instrument includes a dual-ended solid-state detector particle telescope mechanically scanning through 360° across eight equally spaced angular sectors. As reported previously, LECP measurements showed a dramatic increase in GCR intensities for all sectors of the ≥211 MeV count rate (CH31) at the Voyager 1 heliopause (HP) crossing in 2012; however, since then the count rate data have demonstrated systematic episodes of intensity decrease for particles around 90° pitch angle. To shed light on the energy dependence of these GCR anisotropies over a wide range of energies, we use Voyager 1 LECP count rate and pulse height analyzer (PHA) data from ≥211 MeV channel together with lower-energy LECP channels. Our analysis shows that, while GCR anisotropies are present over a wide range of energies, there is a decreasing trend in the amplitude of second-order anisotropy with increasing energy during anisotropy episodes. A stronger pitch angle scattering at higher velocities is argued as a potential cause for this energy dependence. A possible cause for this velocity dependence arising from weak rigidity dependence of the scattering mean free path and resulting velocity-dominated scattering rate is discussed. This interpretation is consistent with a recently reported lack of corresponding GCR electron anisotropies.

Unified Astronomy Thesaurus concepts: Galactic cosmic rays (567); Interstellar medium (847); Heliosphere (711); Heliopause (707); Interstellar magnetic fields (845); Cosmic ray detectors (325)

1. Introduction

Galactic cosmic rays (GCRs) are high-energy charged particles that originate far outside the heliosphere through various mechanisms such as particle accelerations at plasma shocks associated with supernovae or stellar wind collisions (e.g., Ackermann et al. 2013). Although they were discovered in 1912 (Hess 1912), the GCR acceleration mechanisms, composition, filtration and modulation in the interstellar medium and heliosphere are not yet well understood (e.g., Hamaguchi et al. 2018).

Voyager 1 is the first human-made object traveling outside the heliosphere into the very local interstellar medium (VLISM), and hence Voyager 1 charged-particle measurements are critical to determining the source and dynamics of GCRs. Upon exiting the heliosphere on 2012 August 25, the Low Energy Charged Particle (LECP) and Cosmic Ray Subsystem (CRS) instruments observed orders of magnitude decreases in anomalous cosmic rays (ACR) along with significant increases in the GCR count rate (Krimigis et al. 2013; Stone et al. 2013).

Since then, the time series of LECP count rates above ≥211 MeV have exhibited several episodes of reduced proton intensity and time-varying depletion of particles with pitch angles close to 90° (Krimigis et al. 2013; Hill et al. 2020). The pitch angle information from the LECP data indicates a second-order anisotropy, with decreased intensity in the direction perpendicular to the average magnetic field (we delve further into this behavior herein). The anisotropic depletions of GCRs were also accompanied by plasma wave events, weak shocks, and variations in the magnitude of the magnetic field (Gurnett et al. 2015). Similarly, omnidirectional (≥20 MeV) proton-dominated measurements from CRS show up to a 3.8% intensity reduction (Rankin et al. 2019). By analyzing CRS bidirectional (≥70 MeV) and unidirectional (~18 to ~70 MeV) proton-dominated measurements during various spacecraft orientations, including magnetometer roll calibrations and 70° offset maneuvers, they characterized this anisotropy as a “notch” in an otherwise uniform pitch angle distribution of varying depth and width centered about 90° in the pitch angle space. In another study, Rankin et al. (2020) compared GCR ions and electrons. They found very similar profiles for protons in the 30–70 MeV and in the ≥70 MeV energy range, indicating a rather weak energy dependence of these GCR events. Electrons, on the other hand, responded to the shocks in
the same way as ions did, but did not show any noticeable depletion. The reason for this unexpected disparity between the anisotropies of ions and electrons is still an open question (which we address in the Discussion section).

To date, several physical interpretations and models have been proposed to explain these anisotropic features of GCR flux depletion. Roelof et al. (2013) suggest that the anisotropy is due to a trapped configuration between two magnetic field compression regions. Numerical simulations from Jokipii & Kóta (2014) and Kóta & Jokipii (2017) suggest that a gradual compression, followed by a slow weakening of a magnetic field, may account for both the episodic increases and the anisotropic reduction in GCR count rates. While Roelof et al. (2013) recognizes the role of the spatial variation of the magnetic field, Kóta & Jokipii (2017) emphasizes the temporal evolution and the role of adiabatic cooling in the weakening field. A more comprehensive calculation by Zhang & Pogorelov (2020), simulating a spherical shock propagating through the heliopause into the VLISM, reached similar conclusions. This calculation considered only protons at one single energy (100 MeV), and did not address the energy dependence of the GCR event. It is also worth mentioning that Strauss & Fichtner (2014) suggest “heliopause shadowing” as the source of the anisotropy using a model for the perpendicular diffusion coefficient peaking at the 90°. This model predicts a gradual decrease in anisotropy away from the heliopause. In view of unusual timing of these anisotropic variations and transient disturbances in the interstellar medium observed by magnetic field and plasma oscillations, in an observational study using measurements from ACE, New Horizon, and Voyager 1 and 2, Hill et al. (2020) present an alternative escaping particle picture in which a disturbance interacting on only one side of an VLISM field line results in the observed time-dependent anisotropies.

In this work, we present an observational study using Voyager 1 LECP measurements to investigate the anisotropy in GCR fluxes at different energy ranges. The energy dependence of the anisotropy of GCR fluxes can provide essential observational constraints on numerical simulations and theoretical prediction of GCR modulation, filtration, and transport in the VLISM. In Section 2, we provide a brief description of the LECP instrument and different types of measurements used in this study and the techniques we employ in order to quantify the anisotropy. In Section 3, we present our findings on anisotropy at different energy ranges. In Section 4, we provide a summary of this investigation and offer implications of our results in terms of future theoretical development on GCR modulation and filtration in the VLISM.

2. Observations

The LECP on Voyager 1 employs a set of several solid-state detectors, absorbers, and small magnets designed to measure differential intensities of ions from ~40 keV to ~100 MeV nucleons⁻¹ and integral measurements above 211 MeV, and electrons of ~26 keV to ~10 MeV (Krimigis et al. 2003; Decker et al. 2005; Krimigis et al. 2013; Dialynas et al. 2021). Pitch angle information is obtained through mechanical rotation of the detectors. The main detectors look within a single scan plane that is rotated 360°, stopping at eight different look sectors, labeled 1 to 8. The lower-energy detectors have full width view cones of about 45°. Sectors 1 and 5 are aligned approximately perpendicularly to the average magnetic field as measured by the magnetometer instrument (e.g., Burlaga et al. 2020), and hence the data from these sectors correspond to particles with ~90° pitch angle. Note that this approximate alignment of the magnetic field and sectors holds because the direction of magnetic field did not significantly change after the heliopause crossing, as shown in Burlaga et al. (2018).

The LECP instrument consists of two subsystems, the Low Energy Particle Telescope (LEPT) and the Low Energy Magnetospheric Particle Analyzer (LEMPA). In this work, we utilize the data from the LEPT subsystem, as it is termed in the LECP instrument paper (Krimigis et al. 1977), but hereafter we restrict LEPT and HEPT to refer to the low- and high-energy ends of the particle telescope, respectively. The two types of measurements that we use in this study include count rate data and pulse height analyzer (PHA) data. Count rate data at each channel are obtained through analog circuitry (pulse height discriminators and coincidence circuitry) when particles pass through or deposit energy at specific detectors. Detailed PHA “event data” are available for a subset of measured particles, restricted due to telemetry limitations. For this type of data, first the pulse height analysis is completed based on a priority scheme detailed in Krimigis et al. (1977) and Hill (1998), and then energy channel data number (DN) values corresponding to the pulse height are determined by the analog-to-digital converter, which is part of the PHA circuitry. The channel values are indicative of energy deposits in four of the detectors. Hence, while the rate data are determined by onboard LECP analog electronics, PHA measurements are determined based on ground analysis software post-processing and contain detailed information of the amount and location of energy deposited at each detector.

2.1. Unidirectional Flux Correction

The dual-headed nature of the LECP particle telescope introduces some measurement challenges that we need to address in our analysis. For example, the CH31 GCR channel (>211 MeV) on LECP is composed of coincidence measurements from two 2.5 mm thick solid-state detector (D3 and D4) along with anticoincidence measurements from the eight-element, 360° anticoincidence shell. Any particle that deposits energy in these two detectors, but not the anticoincidence shell; hence triggering the analog circuitry will increment the rate count for this channel. Because this telescope is dual-headed, with logic that ignores the signals from the detectors at the entrances of LEPT (D1 and D2) and HEPT (D5), it is not possible to determine the direction of incoming particles in a convectional way, because the desired foreground particles entering from either side produce nearly identical signals in D3 and D4 and less intense signals in the remaining detectors. Here, we describe the procedure that we use to untangle this effect and determine the direction of incident particles. Ignoring the effect of the inactive volume of the instrument (e.g., the housing, electronics, spacers) the geometry of the coincidence and anticoincidence detectors associated with CH31 results in two roughly cone-shaped fields of view, but D3 and D4 are not laterally positioned in the middle of the anticoincidence shell, rather they are offset closer to the HEPT end of the telescope. Because of this offset, the geometry factors for the opposing heads are significantly different \( \frac{g_{D3}}{g_{D4}} \approx 1 \); Roelof et al. 2013). We were able to calculate the geometry factors based on the LECP dimensions and confirm the resulting values using in-flight data during an isotropic
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with a corresponding expression for sector B. Therefore, we are solving these equations for intensities in units of cm

period in the LISM. This analytical technique amounts to solving a linear set of equations as discussed below. Figures 1(a) and (b) show the observational geometry for the incident particles from opposite directions (where \( J_A \) and \( J_B \) represent a pair of anti-aligned aperture-averaged differential intensities in units of cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) MeV\(^{-1}\)) for the LECP eight-sector configuration. \( R \) and \( T \) show two axes from the RTN coordinate system, in which \( R \) is the radius vector from the Sun to the spacecraft, \( T \) is in the direction of solar rotation, and \( N \) completes a right-handed system. The measured, oppositely directed particle counting rates \( r_A \) and \( r_B \) (units of counts s\(^{-1}\)) from the LEPT and HEPT sides (when the motor steps into the opposite, 180° offset configuration) can be written in terms of the constituent intensities and geometric factors \( G_{LO} \) and \( G_{HI} \) (units of cm\(^2\) sr) as

\[
  r_A = J_A G_{HI} + J_B G_{LO},
\]

\[
  r_B = J_B G_{HI} + J_A G_{LO}.
\]

Solving these equations for flux entering the sector A yields

\[
  J_A = \frac{G_{HI} r_A - G_{LO} r_B}{G_{HI}^2 - G_{LO}^2},
\]

with a corresponding expression for sector B. Therefore, we are able to determine the net incoming flux at one direction only when the rates from both oppositely oriented telescope positions are available. We refer to this net incoming flux as unidirectionally corrected flux (referred to as uniflux for the remainder of this article) once the ambiguity in direction is removed. The uncertainty on the uniflux for sector A, \( \sigma_J \), can be computed as

\[
  \sigma_J = J_A \sqrt{\frac{1 + \beta^2}{2 \Delta T} \frac{r_A + r_B}{(r_A - r_B)^2}},
\]

where \( \beta = \frac{G_{LO}}{G_{HI}} \), and \( \Delta T \) notes the exposure time for LECP in the A configuration. We note that this process does assume that the timescale of the GCR intensity variations, especially the anisotropies, is much longer than the timescale of the 360° stepper motor movement. As the former is from many days to 100’s of days and the latter is approximately half an hour, this requirement is easily met.

**2.2. Anisotropy Determination**

The method we employ to determine the anisotropy is a Fourier component technique, where we fit an angular distribution of LECP fluxes to a second-order Fourier expansion following Decker et al. (2005, 2015) as

\[
  j(\phi) = A_0 + A_1 \cos(\phi - \phi_1) + A_2 \cos(2\phi - 2\phi_2).
\]

Note that the reference angle is taken from the \( R \) direction as shown in Figure 2(a).
The $A_0$ is a constant equal to the mean of measurements from all sectors. $A_1$ and $\phi_1$ are the amplitude and phase corresponding to the first-order anisotropy, and $A_2$ and $\phi_2$ are the amplitude and phase corresponding to the second-order anisotropy. Based on the harmonic fit, the first-order anisotropy is associated with the differences between the opposite sectors, while the second-order anisotropy is associated with the differences between a pair of opposite sectors with respect to the remaining sectors.

The fit is conducted over the data from six sectors (1, 2, 3, 5, 6, 7). The data from Sector 8, which holds the Sun shield, and its opposite sector (Sector 4) are not included in the fit. The set of equations in (5) can be solved either analytically or numerically. Figure 2(b) shows a plot of example rate measurements from different sectors (unidirectionally corrected fluxes) with zero mean for CH31 unidirectional fluxes. The data correspond to a 9 day average centered at 2015 November 18. The harmonic fit yields $0.0192 \pm 0.004$ and $327^\circ \pm 8^\circ$ for the amplitude and phase of the first-order anisotropy, and $0.0413 \pm 0.004$ and $89^\circ \pm 2.6^\circ$ for the amplitude and phase of the second-order anisotropy, respectively. The observed azimuthal magnetic field angle is $\sim286^\circ \pm 4^\circ$ (Burlaga et al. 2018) for this time interval, roughly aligned with Sectors 3 and 7 (specifically $106^\circ$ or $286^\circ$ for anti-alignment and alignment, respectively). Therefore, the second-order harmonic angle of $89^\circ \pm 2.6^\circ$ agrees sufficiently (within $17^\circ$, the difference between $106^\circ$ and $89^\circ$) with the interpretation that the depletion of flux (for particles from Sectors 1 and 5) is most significant at $\sim90^\circ$ pitch angles.

2.3. Expansion to Lower-energy Channels

The cosmic ray anisotropies at $90^\circ$ pitch angles in the VLISM at Voyager 1, previously reported by Krimigis et al. (2013) and Hill et al. (2020) using LECP measurements, apply to $\gtrsim211$ MeV (CH31) count rate data. Our work here aims to explore the energy dependence of the GCR; thus we expand our analysis to lower-energy LECP channels, i.e., 5–20 MeV (CH16) and 20.6–200 MeV (CH23). Unlike CH31, both CH16 and CH23 use a coincidence measure from the D5 detector near the HEPT entrance and anticoincidence measurements from the detector beyond the stopping detector and hence do not suffer from the direction ambiguity that required the unidirectional flux correction.

Additionally, we use LECP PHA measurements to further divide each energy range into smaller intervals. For CH31, the incoming particles deposit their energy in the two thick detectors denoted as D3 and D4. Figure 3(a) shows two smaller flux boxes that are being utilized for our analysis for CH31. The measured energy coordinates for these boxes are chosen such that their rates are nearly equal. The two smaller flux boxes for CH23 are overlaid on Figure 3(a). Protons with energies higher than 20 MeV deposit energy on the nominal track of CH23 (box-0). As the energy of the incident particles increases, they deposit their energies on the return track (CH23 box-1), and ultimately particles with energies higher than 211 MeV will deposit their energies on the designated CH31 area on the D4 versus the D3 detector plane. Note that the 40–200 MeV energy range covered in CH23 box-1 is outside of the designed energy range and results from inefficiencies in the anticoincidence veto. Figure 3(b) shows the smaller flux boxes for CH16 on the D5 versus the D4 detector plane. Table 1 provides a summary of Voyager 1 LECP channels, various PHA flux boxes, their corresponding energy range, and their nominal energy labels that we utilize in this study. We note that using the PHA raw data, which include the detailed information on particle-deposited energy and the associated hit position on the detectors, we can post process the data to collect all the box counts in each small flux box and compute the count rates associated with the PHA data, as follows.

\[
r = \frac{X}{P} \frac{C}{\Delta T},
\]

\[
\delta r = r \frac{1}{\sqrt{X}} - \frac{1}{P} + \frac{1}{C},
\]

where $X$, $P$, and $C$ represent the box counts, PHA counts, and channel counts, respectively, and $r$ and $\delta r$ denote the count rate and the associated uncertainty for the PHA data. $\Delta T$ is the exposure time for acquiring data for the corresponding channel.

Note that, even though the different fields of view (FOV) of various channels are unequal, this difference does not affect our
anisotropy analysis. Specifically, CH31 has a wider FOV than CH16 and CH23, because CH31 relies on the 2.60 cm octagonal openings in the anticoincidence shell and the closely spaced pair of detectors, D3 and D4, while the other channels rely on coincidence with multiple 1.65 cm radius detectors (D5 and D4 for CH16 or D5, D4, and D3 for CH23) to constrain the geometry (see Krimigis et al. 1977; Figure 5). The unequal FOV cone angles presents the potential concern that the larger FOV could be the cause of the smaller anisotropy magnitude relative to the lower energies, especially in the “notch” paradigm discussed by Rankin et al. (2019). A close inspection of this potential issue reveals that the effect is negligible because the wide, outer FOV of CH31 (incidence angles from 14° to 48°) has a significantly weaker response than the distinct, narrow-angle inner FOV cone (half angle 14°), while the CH23 and CH16 FOVs do not have narrow-angle inner FOV geometry at all because all detectors are the same size and co-aligned, with a wide angle responses having a half angle of 26°.

3. Results

In this section, we present the anisotropy analysis results for LECP count rates and PHA measurements for the ≥211 MeV (CH31), 5–20 MeV (CH16), and 20.6–200 MeV (CH23) channels, showing the histories of ions with pitch angle close to 90° (Sectors 1/5) together with the time series of ions for the remaining pitch angles (Sectors 2/3/6/7), with “/” used as a delimiter in the list of sectors associated with each average.

Figure 4 shows the time series of averages (over 26 days) of Sectors 1/5 compared with averages from Sectors 2/3/6/7 for the LECP count rate data between 2012 and 2021. Figure 4(a) represents the extended time series of ≥211 MeV channel count rate data (26 days averages) already reported in Krimigis et al. 2013 and Hill et al. 2020, showing a rapid increase in the count rates prior to the heliopause crossing in August 2012 as well as the anisotropic behavior of GCRs in the VLISM. Several episodes of anisotropy, where significant decreases in the Sector 1/5 count rates/fluxes are observed, are illustrated in these plots.

The time series of the 26 day averages of Sectors 1/5 and 2/3/6/7 of 5–20 MeV (CH16) and 20.6–200 MeV (CH23) are shown in Figures 4(b) and (c). We note the significant decrease in the count rates for these channels after the heliopause crossing of Voyager 1. This count rate reduction is more pronounced for 5–20 MeV (CH16) channel, where the count rates drop from ~2 to ~0.05 counts s−1 before and after heliopause crossing, respectively. The gradual decay of 3.4–17.6 MeV proton differential intensities at the heliopause was attributed to a flux tube interchange instability at the boundary (Krimigis et al. 2013), with GCRs slowly leaking out the flux tube into the heliosheath, thus decreasing their fluxes, whereas an outflow of 40–139 keV ions from the heliosheath (perpendicular to the magnetic field; S1 and S5) out to ~28 au past the HP was recently shown in Dialynas et al. (2021). In Figures 4(d) and (e), we adjust the vertical axis range to properly visualize the count rate time variations for 20.6–200 MeV (CH23) and 5–20 MeV (CH16). These plots suggest that the relative time variation of 90° pitch angle particles compared to other pitch angle particles follows that of CH31 closely. The cyan lines in these plots indicate the average of nonperpendicular pitch angles after heliopause crossing to emphasize the depletion of perpendicular pitch angle particles. The uncertainty levels of measurements are also noted. Due to the decreased count rates, the relative error bars are higher for lower-energy channels measurements compared to ≥211 MeV channel data.

The ratios of the data from Sectors 1/5 over those of Sectors 2/3/6/7 for the three channels are shown in Figure 5. The time series of the 5–20 MeV channel (CH16) ratios shows the largest variability compared to those of other channels. This higher variability is due to the significantly lower count rates for CH16 (see the discussion of Figure 9(c), which describes why the CH16 rate by itself should not be relied upon for anisotropy). At the heart of the anisotropy episodes, the 20.6–200 MeV channel (CH23) seems to exhibit the smallest count rate ratio. Albeit these ratios provide a direct indication of the anisotropic behavior for the 90° pitch angle particles, they do not provide angular information. Figures 5(b) and (c) show the normalized second-order anisotropy amplitude (A2/A0) and phase (φ2), respectively. The normalized anisotropy amplitude is smallest for the CH31 rate data. The respective parameter is typically highest for CH23 while the associated variability is largest for CH16. The second-order anisotropy angle is centered close to 90° during the identified anisotropy episodes (as shown in Figure 4(a)): 2013-01 to 2013-08, 2014-01 to 2014-08, 2015-01 to 2016-12, and 2018-04 to 2020-01, showing a small variation as appropriate for a well-constrained harmonic fit. Note that the dates are shown in the year-month format.

Next, we present the anisotropy results for the PHA data, big flux box measurements. The count rate for the big flux boxes is computed from the sum of small flux boxes parameters (which are accumulated over averaging interval): box counts (N), PHA counts (P), channel counts (C), and exposure time (ΔT), where i indexes each flux box, as

\[
r = \frac{\sum_i N_i}{\sum_i P_i} \frac{\sum_i C_i}{\sum_i \Delta T_i},
\]

with the small boxes shown in Figures 3(a) and (b) for CH31, CH23, and CH16. Similar to Equation (7), the uncertainties are computed as

\[
\delta r = r \sqrt{\frac{1}{\sum_i N_i} - \frac{1}{\sum_i P_i} + \frac{1}{\sum_i C_i}}.
\]
Figure 6 shows 26 day averages of measurements from Sectors 1/5 and Sectors 2/3/6/7 for the big flux box measurements of \( \geq 211 \text{ MeV} \) (CH31), 20.6–200 MeV (CH23), and 5–20 MeV (CH16) count rates. While the general trend of the time series matches that of the rate measurements, the measured uncertainties (computed from Equation (9)) are significantly higher compared to the rate data, as expected. As explained earlier (Figure 4), the range on the vertical axis in Figures 6(b) and (c) is adjusted for the proper visualization of the data after heliopause crossing.
The ratio of measurements from Sectors 1/5 over Sectors 2/3/6/7 PHA big flux box data is shown in Figure 7(a), whereas the corresponding normalized amplitude and angle of the second anisotropy are shown in Figures 7(b) and (c), respectively. Similar to Figure 4, averages of Sectors 1/5 (perpendicular to the average magnetic field) and averages of Sectors 2/3/6/7 are shown with blue and orange, respectively.

The ratio of measurements from Sectors 1/5 over Sectors 2/3/6/7 PHA big flux box data is shown in Figure 7(a), whereas the corresponding normalized amplitude and angle of the second anisotropy are shown in Figures 7(b) and (c), respectively. Similar to the rate data (Figure 5), the 20.6–200 MeV (CH23) big flux box data show a higher degree of anisotropy over short periods at the heart of the anisotropy episode (see the discussion of Figure 9(c), which describes why, similar to the CH16 rate data, the CH16 big flux box by itself should not be relied upon for anisotropy analysis). The data from the ≥211 MeV (CH31) channel exhibit the least anisotropic behavior. As a minor distinction between the two figures, we note higher uncertainty levels of the estimated PHA count rate ratios as well as second-order anisotropy parameters. This is due to the aforementioned telemetry limit on PHA event data compared to the rate data, resulting in fewer counts in comparable PHA event-based quantities.

Finally, we examine the anisotropy of the Galactic cosmic rays for the small PHA flux box count rates (Figure 3). In order to ensure credible statistics with the relatively limited PHA events, we compute averages of the data for longer time periods. The breakdown to smaller flux boxes allows for investigation of the time series trends of the 90\(^\circ\) pitch angle particles with even finer energy resolution. An example is given in Figure 8, where the time series of the data for different energy channels of small flux boxes, 0 (left column) and 1 (right column), averaged over 200 days, are shown. Considering Figures 8(a) and (b), we find that the count rate depletion of Sectors 1/5 associated with ~500 MeV (CH31 box-0) is more significant than that of ~1000 MeV (CH31 box-1).
the rate and big flux box data, we note a significant count rate reduction in the measurements from the two flux boxes of 20.6–200 MeV (CH23; Figures 9(c) and (d)), and an additional reduction in the two flux boxes of 5–20 MeV (CH16; Figures 9(e) and (f)). Moreover, we observe a slight reduction in the count rates for the data corresponding to the lower-energy flux box-0 compared with the higher-energy flux box-1 for all three energy channels. Figures 8(e) and (f) show lower
count rates for Sectors 1/5 compared to Sectors 2/3/6/7, especially during the period around mid 2014 to 2017, although the timings of the reductions do not quite match with each other (we discuss a possible explanation for this misalignment later in this section).

Figure 9 illustrates the ratios of the measurements from Sectors 1/5 over those from Sectors 2/3/6/7 for the six small flux boxes. Similar to the plots from Figures 5 and 7, the ratios from the two CH31 flux boxes are typically higher compared to those from other channels. Breaking down to small flux boxes reveals an approximately 4% increase in the ratios for ~1000 MeV protons (CH31 box-1) compared to the lower-energy portion ~500 MeV (CH31 Box-0). The smaller ratios for CH23 25 and 90 MeV flux boxes compared to those of CH31 flux boxes during the anisotropy episodes are in agreement with the count rate data (Figure 5) and big flux measurements (Figure 7). The major difference in this case is that, unlike the count rate and big flux box data, the ratios for CH16 box-0 (7 MeV) and CH16 box-1 (13 MeV) in Figure 9(c) are considerably smaller reaching down to 0.8 for two anisotropy episodes (2013 and 2016 episodes). These lower ratios indicate a higher level of anisotropy at lower energies.

As explained below, the analog energy threshold circuitry has the effect of preferentially excluding particles with incidence angles close to normal that are counted in CH16 box-1, and that makes direct comparison of data from this flux box more complicated. The reason that the second-order anisotropy amplitudes are lower for CH16 compared to CH23 for count rate data and big flux measurements is that both these data types include the data from CH16 box-1. Therefore, any complications associated with CH16 box-1 will affect the analysis results, especially because the rate in CH16 box-1 is much higher than CH16 box-0.

In the final part of this section, we employ Voyager 1 small flux box measurements to present the energy dependence of Galactic cosmic rays for three different anisotropy episodes. Following the methodology mentioned above, we first sum all the box counts, channel counts, PHA counts, and exposure time, and compute the count rates based on Equation (8). We then compute the unidirectionally corrected fluxes for the CH31 flux boxes and apply the fit to determine the second-order anisotropy parameters.

Figure 10 presents the second-order normalized amplitude (left column) and angular (right column) anisotropy for three anisotropy episodes as indicated in Figure 4(a), i.e., 2013-01 to 2013-08, 2015-01 to 2016-12, and 2018-04 to 2019-06. Panels (a) and (b) illustrate the estimated anisotropy parameters for the episode between 2013-01 and 2013-08, which is about 212 days long. With the exception of CH16 box-1 (~13 MeV), the normalized amplitudes carry a decreasing trend with increasing energy, and the angular phase of the anisotropy is ~95° ± 10° (equivalently 275° ± 10° as the second harmonic is periodic over 180°). This result is in reasonable agreement (within error bars) with the azimuthal magnetic field of ⟨λ⟩ = 292.5° ± 1.4° (Burlaga & Ness 2016). The anisotropy parameters from CH16 box-1 do not quite agree with those from other flux boxes and seem to be more isotropic during this episode with an estimated second-order anisotropy angle of 45° ± 43°, and a normalized amplitude of 0.018 ± 0.022. The likely explanation for this peculiar behavior is that the CH16 box-1 has an energy threshold that cuts through the track “horizontally” (at a constant D5 value as shown in Figure 3(b)); hence particles with small incidence angles can be preferentially excluded. More specifically, the vertical (D5) energy spread in the track is caused in part by the varying angles of incidence of particles entering the HEPT end of the telescope, where larger energy deposits correspond to larger angles relative to the normal incidence. The trajectories of larger incident angles typically result in longer paths through the detectors, with proportionately more interactions between the incident particle and the silicon crystal, which in turn result in a larger energy deposit. Therefore, particles closer to normal incidence for a given sector are preferentially excluded by the interfering energy threshold, thus complicating direct comparisons between CH16 box-1 and any other boxes. To test whether this effect is large enough to explain the peculiar CH16 box-1 behavior, we conducted simple GEANT simulations (Agostinelli et al. 2003) of the D5 and D4 detector pair, simulating 10,000 protons, with energies E in the 1–30 MeV range and intensity spectra with an ~E–1.5 dependence. We performed six runs, covering angles of incidence from 0° to 25° (steps of 5°) relative to normal. These simulations confirmed our expectations and allowed us to estimate an approximately 40% D5 energy spread across the full 0° to 25° incident angular span. We also estimated an intensity error of as high as approximately 20% for a test case, which is sufficient to invalidate the measurements. Thus we have to rely on box-0 of CH16, despite the reduced statistics relative to box-1. This result also explains why the CH16 big flux box and rate data are not completely reliable, especially for anisotropic features smaller than the FOV.

The episode from 2015 to 2016 is the longest anisotropy episode. While the anisotropy phase is relatively close to 90° for all energies, confirming the depletion of the signals for the perpendicular pitch angle particles at all energies, the normalized amplitude decreases with increasing energy (panels (c) and (d)). The measurements from the two flux boxes associated with CH31 show the smallest normalized second-order amplitudes with 0.029 ± 0.01 and 0.017 ± 0.006 for ~500 MeV (CH31 box-0) and ~1000 MeV (CH31 box-1), respectively. Panels (e) and (f) of Figure 10, show the estimated parameters for the anisotropy period between 2018-04 to 2019-06. For this time interval, too, the normalized amplitudes are the smallest for the CH31 flux boxes, while the amplitudes for the lower-energy channels are approximately the same with relatively higher error bars. With the exception of CH16 box-1, all estimated phases of the second-order anisotropy during this third period are smaller (an average of 88°) compared to the other two time intervals. This agrees well with the declining trend in the azimuthal magnetic field angle given in (Burlaga et al. 2020).

The linear fits to the normalized amplitudes have slopes of −0.0143 ± 0.0077, −0.0153 ± 0.0038, and −0.0168 ± 0.0047 in panels (a), (c), and (e), respectively. The negative slopes indicate a decreasing trend for the normalized amplitude with increasing energy for all three anisotropy episodes.

4. Discussion

We provided a detailed observational investigation of the Galactic cosmic ray anisotropies in the VLISM as a function of the energy, using the Voyager 1 LECP observations. The results of this study can be summarized as follows:

1. Systematic episodes of intensity decreases for ~90° pitch angle particles were reported in Voyager 1 LECP ≥211 MeV count rate measurements. To gain a better understanding of the anisotropy behavior as a function of
the energy, we use count rates as well as PHA measurements from various LECP channels.

2. Although CH31 ($\geq 211$ MeV) is a dual-headed telescope, using the different geometry factors associated with the two sides, we are able to estimate directional fluxes.

3. We apply a Fourier harmonic technique to quantify the anisotropy behavior. This technique is enabled by the pitch angle information that the LECP instrument provides.

4. Both the rate data and big flux box PHA measurements show a larger second-order anisotropy for the LECP lower-energy channels ($\leq 90$ MeV) compared to the LECP ($\geq 211$ MeV; CH31) unidirectionally corrected measurements.

5. For the LECP integral channel CH31 ($\geq 211$ MeV), the rebinning of PHA shows a larger anisotropy for energies $\sim 500$ MeV compared to $\sim 1000$ MeV, driven by the behavior of the ions perpendicular to the magnetic field.

6. The rebinning of the LECP PHA boxes to small flux box data reveals a stronger anisotropic behavior for low-energy ions ($\sim 10$–$20$ MeV).

7. The anisotropy analysis of small flux box data over three anisotropy episodes of 2013-01 to 2013-08, 2015-2016,

![Figure 10. Second-order anisotropy parameters as a function of the energy during three anisotropy episodes: 2013-01 to 2013-08, 2015-2016, 2018-04 to 2019-06. The left column ((a), (c), (e)) shows the normalized amplitude, whereas the right column ((b), (d), (f)) provides the angular information for the second-order anisotropy. The dashed red line in each plot shows a linear fit to the data. The linear fits for the normalized amplitude as a function of the logarithm of energy have slopes $-0.0143$, $-0.0153$, $-0.0168$ in panels (a), (c), (e), respectively. The negative slopes indicate a decreasing trend for the normalized amplitude with increasing energy for the three anisotropy episodes. The linear fits for the second-order anisotropy angle show near horizontal lines limited between 90° and 110° for all three anisotropy episodes confirming the depletion of particles perpendicular to magnetic field.]

![Figure 10. Second-order anisotropy parameters as a function of the energy during three anisotropy episodes: 2013-01 to 2013-08, 2015-2016, 2018-04 to 2019-06. The left column ((a), (c), (e)) shows the normalized amplitude, whereas the right column ((b), (d), (f)) provides the angular information for the second-order anisotropy. The dashed red line in each plot shows a linear fit to the data. The linear fits for the normalized amplitude as a function of the logarithm of energy have slopes $-0.0143$, $-0.0153$, $-0.0168$ in panels (a), (c), (e), respectively. The negative slopes indicate a decreasing trend for the normalized amplitude with increasing energy for the three anisotropy episodes. The linear fits for the second-order anisotropy angle show near horizontal lines limited between 90° and 110° for all three anisotropy episodes confirming the depletion of particles perpendicular to magnetic field.](#)
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Table 2
Summary of the Second-order Anisotropy Amplitude (normalized) and Phase Variation (degrees) as a Function of Energy for the Three Anisotropy Episodes Noted in Figure 10

| Anisotropy Episode | Particle Energy | 7 (MeV) | 13 (MeV) | 25 (MeV) | 90 (MeV) | 500 (MeV) | 1000 (MeV) |
|--------------------|-----------------|---------|----------|----------|----------|----------|-----------|
| 2013-01 to 2013-08| Amplitude       | 0.097 ± 0.031 | 0.017 ± 0.030 | 0.050 ± 0.023 | 0.045 ± 0.011 | 0.037 ± 0.008 | 0.028 ± 0.008 |
|                   | Phase           | 94.2° ± 10.0° | 45.9° ± 48.5° | 88.7° ± 12.6° | 98.2° ± 8.6° | 96.3° ± 7.1° | 91.2° ± 8.5° |
| 2015-01 to 2016-12| Amplitude       | 0.057 ± 0.020 | 0.035 ± 0.012 | 0.049 ± 0.016 | 0.042 ± 0.026 | 0.029 ± 0.010 | 0.017 ± 0.006 |
|                   | Phase           | 97.8° ± 12.0° | 93.2° ± 12.2° | 102.6° ± 8.1° | 86.2° ± 15.9° | 91.7° ± 9.4° | 92.6° ± 10.7° |
| 2018-04 to 2019-06| Amplitude       | 0.046 ± 0.028 | 0.047 ± 0.025 | 0.037 ± 0.034 | 0.058 ± 0.023 | 0.025 ± 0.008 | 0.017 ± 0.007 |
|                   | Phase           | 73.5° ± 12.9° | 149.2° ± 11.5° | 76.9° ± 20.4° | 101.1° ± 14.8° | 92.5° ± 9.8° | 89.3° ± 12.1° |

2018-04 to 2019-06 showed a decreasing trend in the amplitude of second-order anisotropy with increasing energy with slopes of $-0.0143 ± 0.0077$, $-0.0153 ± 0.0038$, $-0.0168 ± 0.0047$, respectively.

Table 2 summarizes the results for the energy dependence of the second-order anisotropy amplitude and phase for these anisotropy episodes.

Numerical simulations (e.g., Jokipii & Kóta 2014; Kóta & Jokipii 2017) provide evidence that these anisotropies might be related to the heliosphere transient events indicating that gradual compression, followed by a slow weakening of the magnetic field, may account for the pitch angle GCR anisotropic decreases. According to the model, particles near 90° pitch angles become trapped and cool down in the expanding field. The longer they are trapped, the more energy they lose, resulting in reduced intensity, where the spectrum is falling. The magnetic field observed at Voyager 1 has decreasing trends during the depletion events (see Gurnett et al. 2015), which suggest that the depletion of GCRs is connected with the weakening of the field. For brevity, the model uses several simplifying assumptions, some of which may not hold for the long-lasting depletion events. The magnitude of the depletion is expected to depend on the spectral exponent of GCRs; a steeper spectrum should result in larger depletion.

The Kóta & Jokipii (2017) model considers purely magnetosonic variations in a simplified field geometry, which could also lead to some modifications in the resulting GCR depletion. More importantly the model assumes scatter-free motion of GCRs along the magnetic field lines so that the adiabatic invariant $p^2/v/B$ remains conserved. This assumption might lead to the inability of the model to predict any energy dependence for the resulting anisotropy. We note that the more complex simulation of Zhang & Pogorelov (2020) includes a weak scattering too. This work, however, considered only protons at one single energy (100 MeV) and did not address the energy dependence.

The primary result of our analysis is the identification and characterization of the energy dependence of the anisotropy for Voyager 1 GCR ions during the anisotropy episodes in the VLSM. It is notable that although this energy dependence is pronounced in protons, the relationship of the model to kinetic and mass is not at all clear as Rankin et al. (2020) found that 3–105 MeV electrons do not exhibit any evidence of episodic anisotropy variations. The disparity between ions and electrons is still posing an unresolved challenge. Fluctuations in the outer heliosheath and very local interstellar medium may result in sufficient pitch angle scattering (Florinski et al. 2021) that could decrease the amplitude of the anisotropic depletion of GCRs. However, most of observations and theories indicate that electrons tend to suffer less scattering than ions. In the lack of more plausible interpretations, Rankin et al. (2020) raised the possibility that, according to some indications, electrons may scatter through a 90° pitch angle more efficiently than ions do. Here, we suggest an additional scattering-related process that may result in predominantly velocity-dependent anisotropy, consistent with our observations. Considering that the rate $v$ of pitch angle scattering (for isotropic scattering) scales as velocity $v$ over the mean free path $\lambda$, (where $\lambda$ depends in general on rigidity), we obtain a scattering rate dominated by the velocity if the rigidity dependence of the mean free path is weak. In the limit of a rigidity-independent mean free path, the scattering rate becomes proportional to the velocity with the mean free path setting the constant of proportionality: thus $v = v/\lambda$ (Chapman & Cowling 1958). The physical interpretation, put simply, is that for a constant mean free path the faster particles experience more frequent scattering than the slower particles, and this serves to increasingly obscure the anisotropy as velocity increases, which means that the very fast electrons would show little anisotropy and the much slower protons would show more anisotropy, but with faster (and higher-energy) protons showing a decreasing anisotropy as a function of energy, as we observe. A preliminary analysis of Voyager 2 LECP observations also reveals a reduction in intensity for the 90° pitch angle particles after the heliopause crossing in 2018. A more complete study of Voyager 2 observations is required to fully explain the energy dependence of the anisotropies.

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