PROCEEDINGS OF SCIENCE

The Anisotropy of Anomalous Cosmic Rays Observed by Voyager 2 in the Heliosheath

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Voyager 2 (V2) has been observing anomalous cosmic rays (ACRs) in the heliosheath since August 2007 when V2 crossed the termination shock of the supersonic solar wind. We use the counting rate of ∼0.5-35 MeV protons collected during periods when the spacecraft was rolling about the axis pointed to the Earth to infer their direction of flow. The observed flow velocity is the combination of the flow due to motion of heliosheath plasma and a diffusive flow due to a gradient in the ACR intensity. The latitudinal component of the flow (N component) agrees with the convective flow due to the heliospheric plasma flow as determined by the plasma instrument on V2. However, the tangential component of the flow (T component) is smaller than the predicted convective flow, consistent with an intensity gradient in the +T direction and a diffusive flow of ACRs from a source located in the +T direction. This would be consistent with models predicting that the acceleration of higher energy ACRs occurs along the flanks or tail of the heliosphere. A similar result was obtained by analysis of the V1 magrol data during V1's journey through the heliosheath [1].

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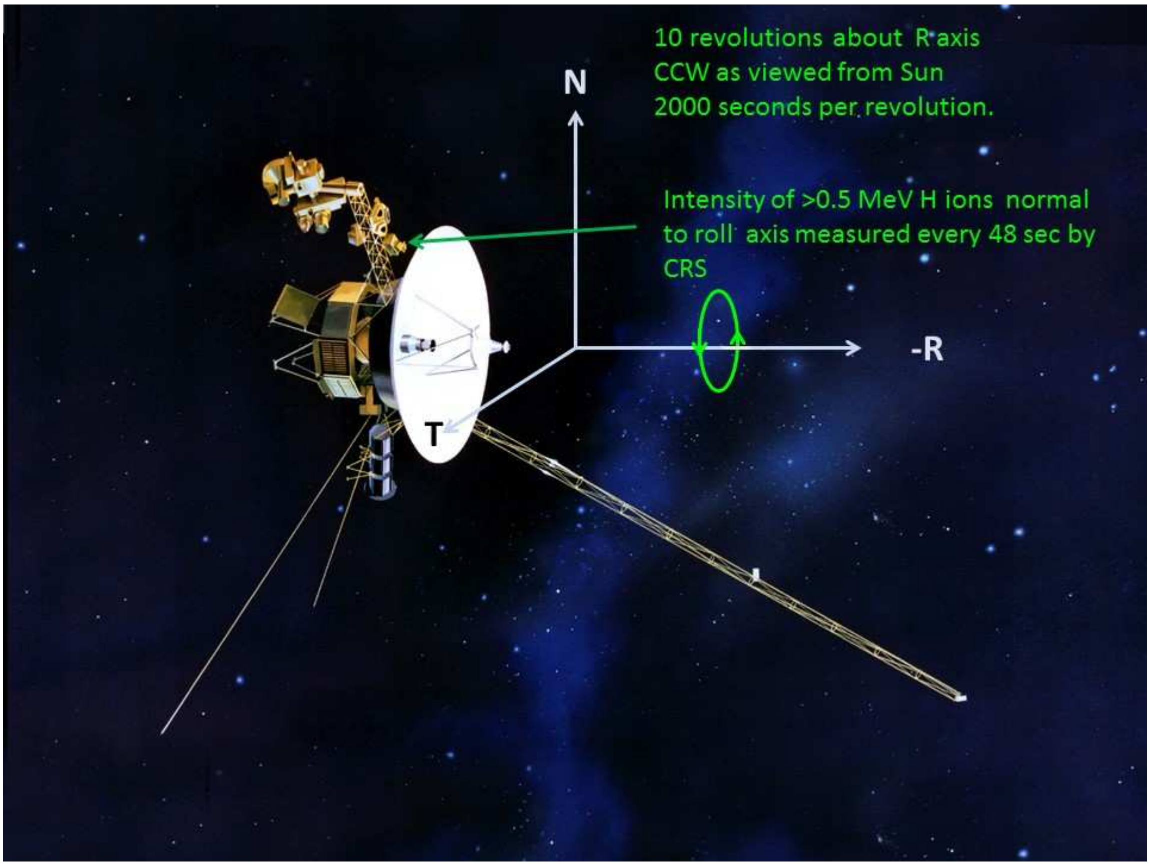

Figure 1: Voyager spacecraft with RTN coordinate system superimposed. The spacecraft is normally three-axis stabilized with the high-gain antenna pointed towards Earth. The -R axis points towards the Sun, and in the outer heliosphere beyond 100 AU, the difference between the -R axis and the antenna axis is less than 1°. The CRS LET telescopes are able to measure the anisotropy of 0.5 - 35 MeV protons in the T - N plane every several months when the spacecraft is rolled about the antenna axis.

1. Introduction

When Voyager 1 and Voyager 2 crossed the termination shock they did observe the expected increase in Anomalous Cosmic Rays, indicating their source was elsewhere on the shock or in the heliosheath. If the source is in the nearby flank region [2, 3, 4], the resulting diffusive flow would contribute to a field-aligned anisotropy that is opposite to that produced by the Compton-Getting effect (see, e.g. [5]) as the plasma turns toward the heliospheric tail. Decker et al. [6] used the anisotropy δ observed by LECP to determine the plasma velocity **V** according to $\mathbf{V} = v\,\delta/(-2(1-\gamma))$, where v is the speed of the energetic particles and the spectral index for the energetic particles is $\delta = d \ln j / d \ln E$.

2. Observations

Voyager 1 and 2 have fixed attitudes and the CRS detectors are body-fixed. However, calibrations of the magnetometer requires rolling the spacecraft about the axis of the high gain

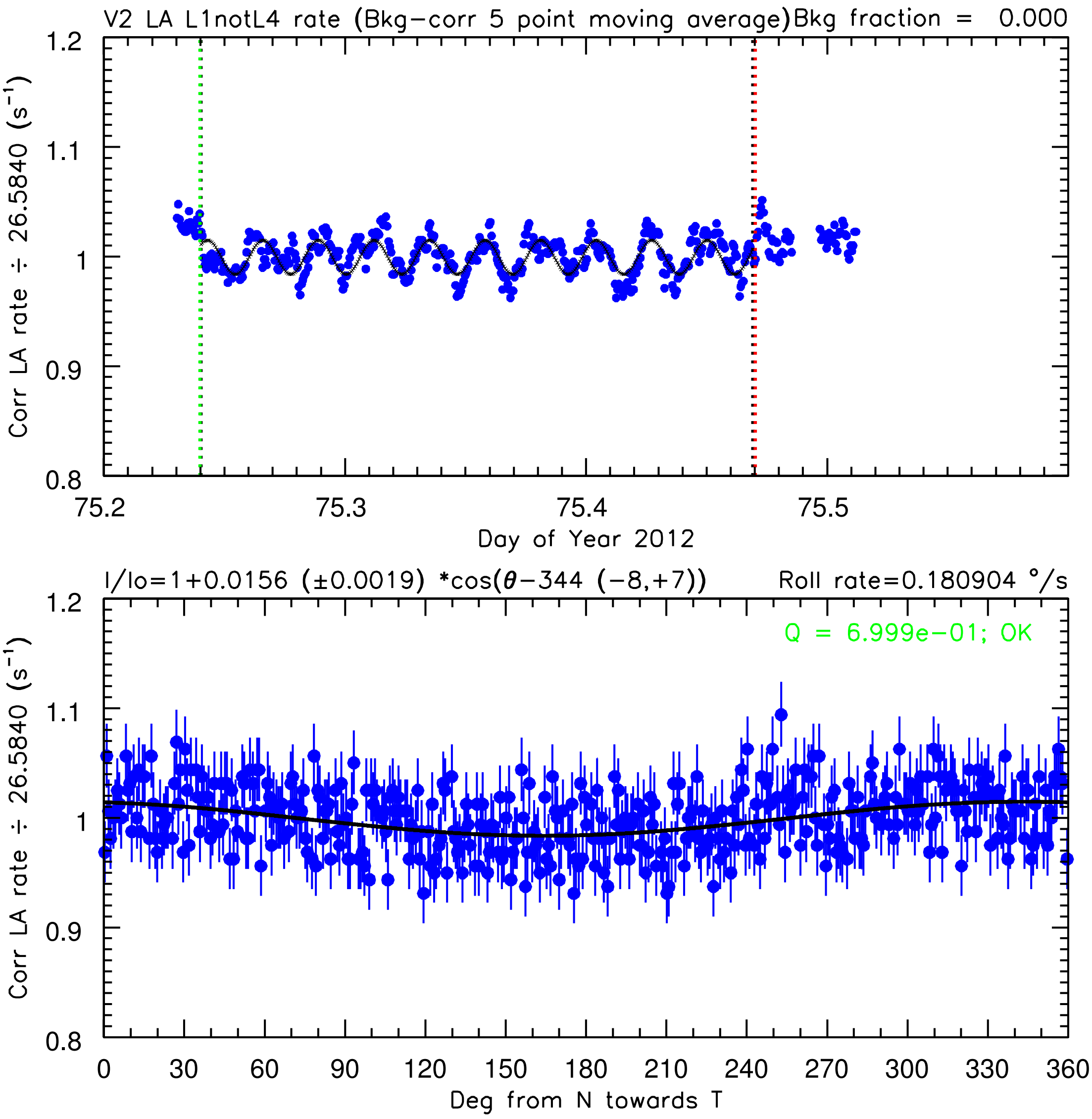

Figure 2: V2 LET A1 counting rate of mainly protons with 0.5 to 35 MeV during ten spacecraft rolls on day 75 of 2012. In the upper panel the points are 5-point moving averages, where each point represents data collected over a 48-second time period. In the bottom panel, each 48-second point is plotted individually vs. the telescope boresight angle projected into the T-N plane. The N axis is at 0° and the T axis is at 90°. The solid lines in both panels represent a best fit of the 48-second data to the function $I_0(1+\delta\cos(\theta-\theta_0))$. The parameter Q is the chi square statistic and the fit is declared to be OK if Q falls in the range of 0.05 to 0.999.

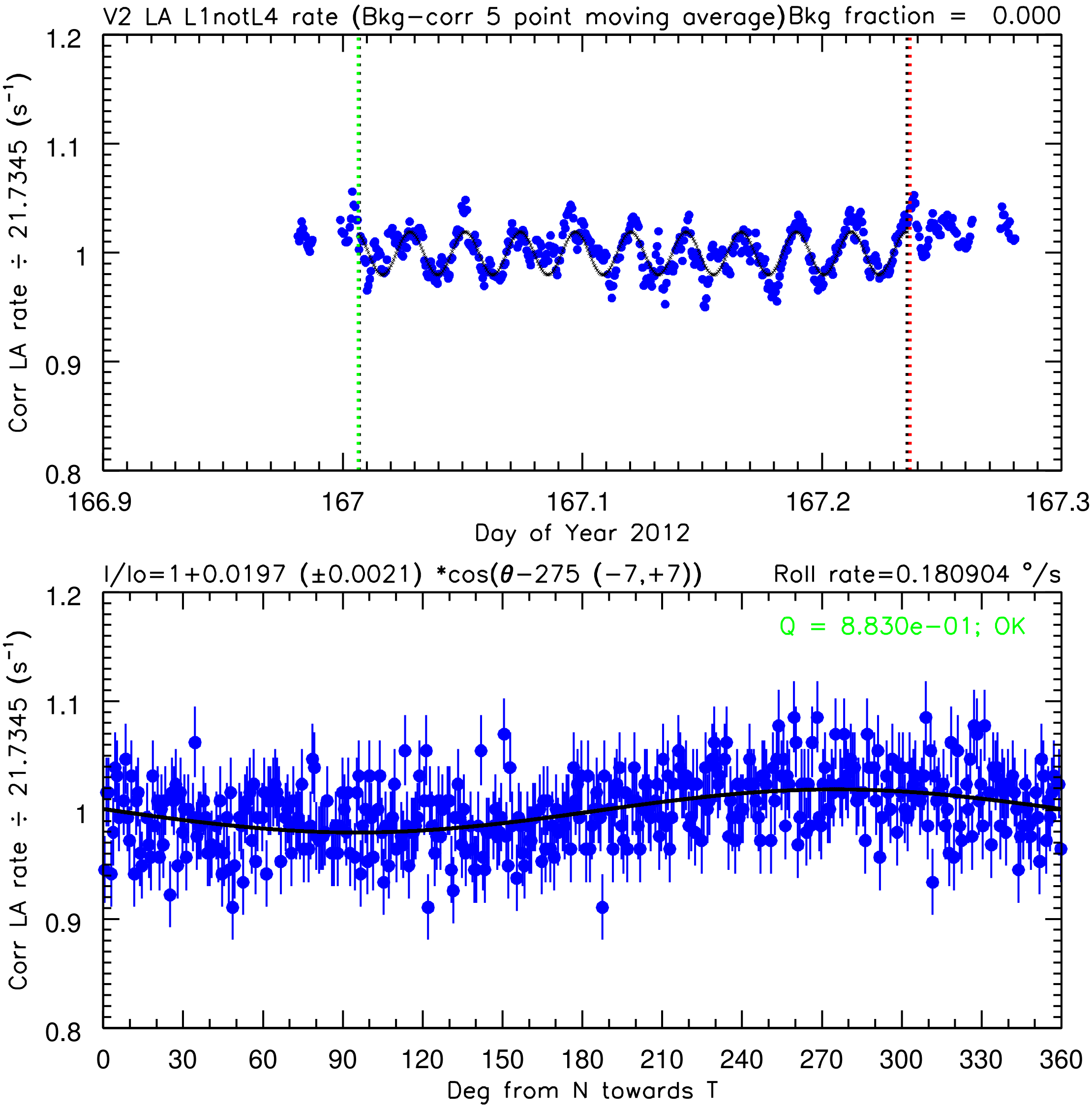

Figure 3: Same as Figure 2 except data are from day 167 of 2012.

antenna every several months (Figure 1). Each calibration is 10 complete rolls lasting 20,000 seconds. The antenna axis is closely aligned with the -R direction in the RTN coordinate system, making possible anisotropy determination in the T-N plane during the rolls by measuring the variation in the counting rate in the front detectors in the Low Energy Telescopes (LET A, LET B, and LET D). Each front detector (LA1, LB1, and LD1) has a geometry factor of 4.75 cm^2 sr, an acceptance angle of 120°, and a sampling time of 48 seconds after day 2011/217. The counting rates are mainly due to protons with 0.5 to 35 MeV.

Figure 2 shows the LA1 count rate variation during a set of 10 rolls on 2012 day 75. The temporal variation during the 10 rolls is apparent in the upper panel, while the lower panel shows the 48-second data points from all 10 rolls as a function of θ, the telescope boresight angle counterclockwise from N in the T-N plane as viewed from Earth. The data in the lower panel

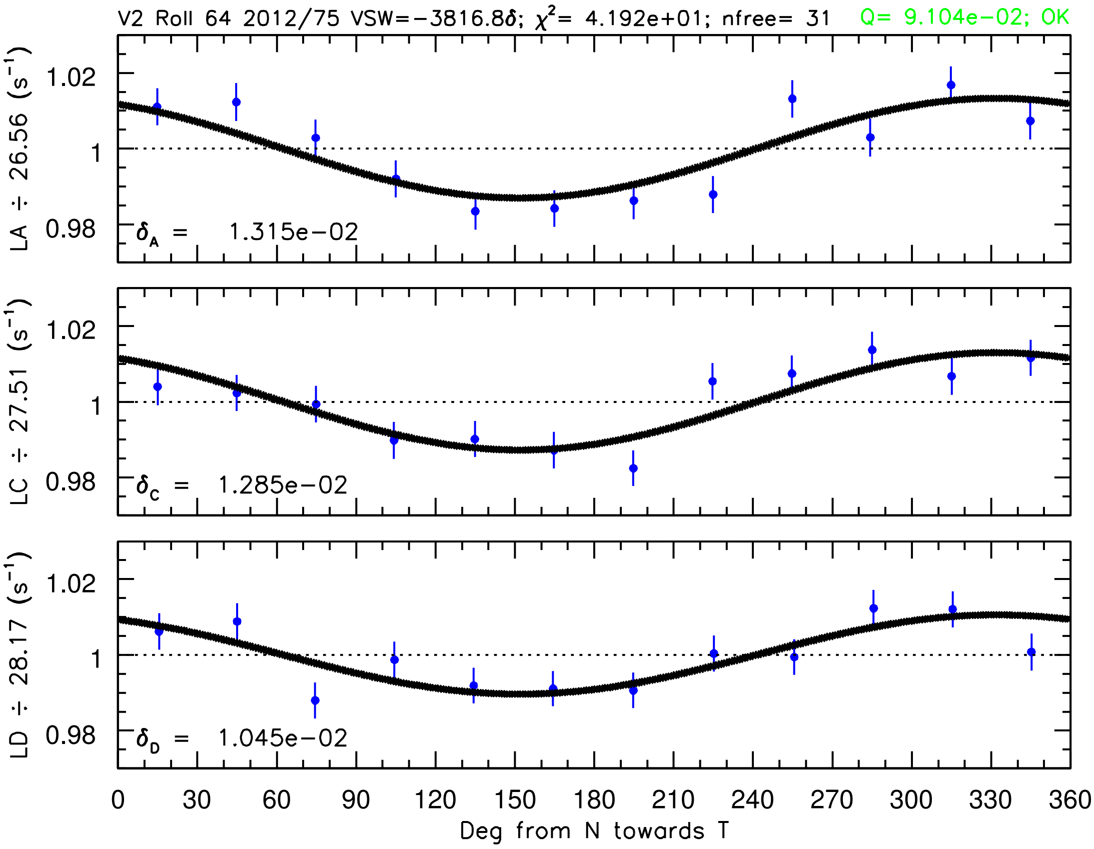

Figure 4: Counting rate of mainly protons with 0.5 to 35 MeV from the V2 LET A, LET B, and LET C telescopes averaged in 30° sectors in boresight angle projected into the T-N plane for the ten spacecraft rolls on day 75 of 2012. The solid lines are fits to $I_0(1+\delta\cos(\theta-\theta_0))$. The best-fit anisotropy amplitudes, δ, are shown in each panel. The conversion from δ to convective solar wind speed in km/s, VSW, is shown at the top of the figure. The conversion factor includes a 20% correction for the 120° opening angle of the telescope aperture.

are fit with a first order anisotropy function $I/I_0 = 1+\delta\cos(\theta-\theta_0)$, where θ_0 is the boresight angle at which the intensity maximum occurs. The best fit for 2012 day 75 yields δ = 0.016 $\pm$ 0.002 and θ_0 = 344 $\pm$ 8. Figure 3 shows similar results for day 2012/167 where the best fit yields δ = 0.020 $\pm$ 0.002 and θ_0 = 275 $\pm$ 7. This indicates there is significant variation in the amplitude and direction of the anisotropy.

If the energetic particle anisotropies are due to convection of the heliosheath plasma, the convection velocity is given by **V** = -1.2 K_{CG} δ, where K_{CG} = <v/(2(1-γ))> is averaged over the proton energy spectrum between 0.5 and 35 MeV [1]. The factor of 1.2 corrects for the reduction in the maximum anisotropy caused by averaging over the large acceptance angle of 120°. With K_{CG} = 4000 km/s, an uncertainty of $\pm$ 0.002 in the observed δ introduces an uncertainty of $\pm$10 km/s in the derived convective velocity V.

Intensity data from all three LETs were fit by this Compton-Getting relationship in order to estimate the V_T and V_N components of the convective velocity. In making the fits, V_R was fixed to

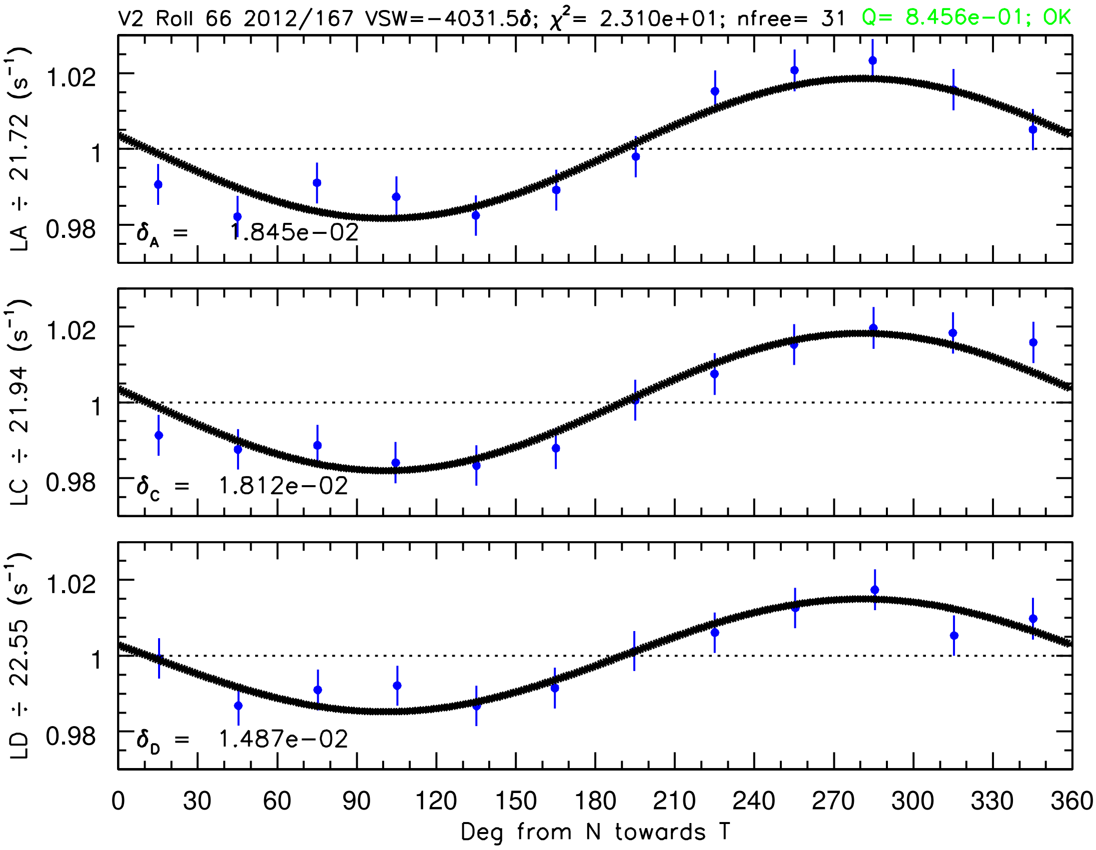

Figure 5: Same as Figure 4 except data are from day 167 of 2012.

that measured by the PLS plasma instrument. The determinations of the V_T and V_N were insensitive to changes in the assumed V_R, varying less than 0.3% with changes of a factor of 2 in V_R. Figures 4 and 5 show examples of the anisotropy fits for days 2012/75 and 2012/167. If these are Compton-Getting anisotropies, the derived convective velocities are V_T = 26 km/s and V_N = -49 km/s on 2012/75 and V_T = 80 km/s and V_N = -15 km/s on 2012/167. These derived convection velocities and similar analyses of 19 other roll calibrations are shown in Figure 6 for comparison with the velocities measured by PLS.

3. Results and Summary

As shown in Figure 6, the CRS derived V_N is typically about -50 km/s in fair agreement with the observed plasma flow. There is one period in 2015 where the CRS derived speed +50 km/s is opposite to that observed by PLS, indicative of a transient non-convective flow of energetic particles. That transient event is also apparent in the CRS derived V_T of nearly 200 km/s that is about twice the V_T that typically observed by PLS.

Unlike the fair agreement in V_N, the CRS-derived V_T is typically about half of that observed by PLS and more variable, suggesting that there is a diffusive flow of MeV energetic particles in the -T direction that is opposite to the PLS convective flow in the +T direction. However, the V_T

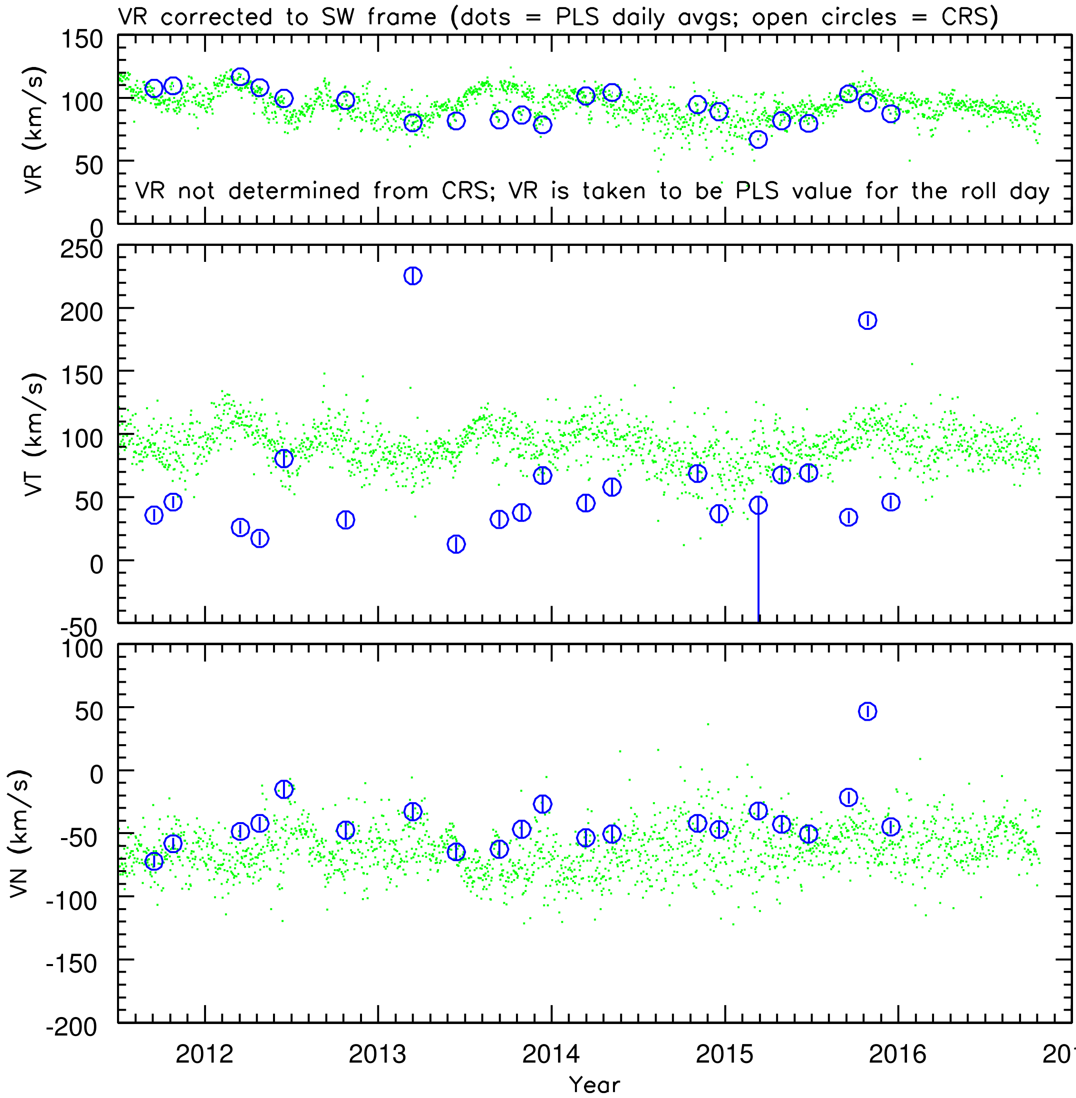

Figure 6: T and N components of the solar wind vector (middle and bottom panels) deduced from the V2 CRS spacecraft roll data (open circles), samples of which are shown in Figures 4 and 5. The radial component (top panel) is not calculated from CRS data; instead a daily-averaged value is used from the V2 PLS instrument and corrected to the spacecraft frame by subtracting the speed of V2. The dots in each panel are values of the components from the V2 PLS instrument.

determined by LECP at 28-43 keV is generally in good agreement with LECP [7], indicating that a diffusive flow is not typically observed by LECP at lower energies. This suggests that the 28-43 keV ions are being radially convected from the termination shock, while the higher energy anomalous cosmic rays are diffusing from the flank tail region as proposed by [2, 3, 4] and suggested by Stone and Cummings from Voyager 1 data [1].

Acknowledgments

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